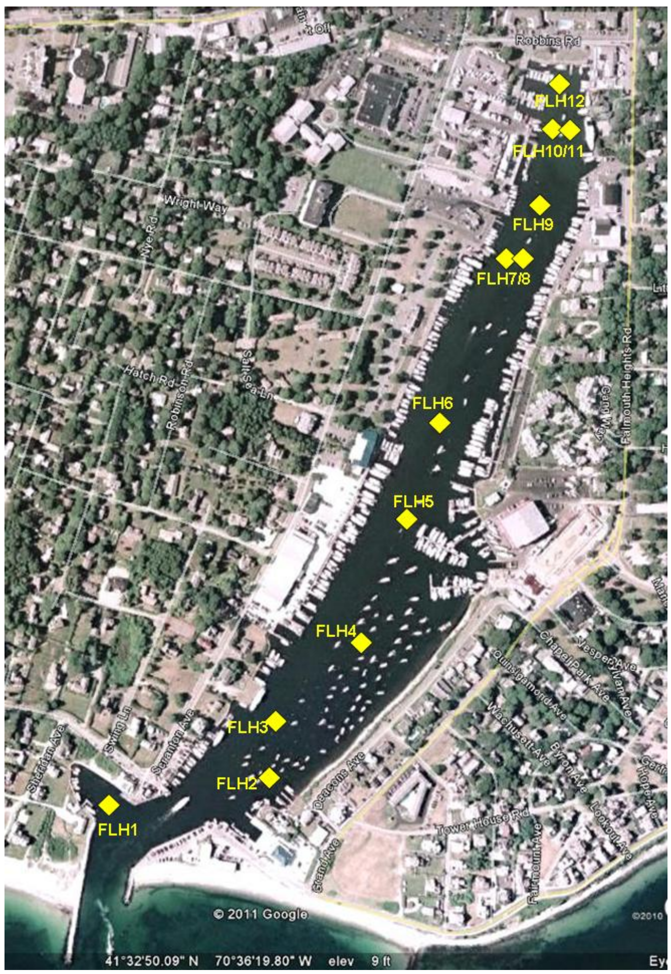
Massachusetts Estuaries Project

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



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

FINAL REPORT – March 2013

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Linked Watershed-Embayment Approach to Determine Critical Nitrogen Loading Thresholds for the Falmouth Inner 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 Falmouth Inner Harbor embayment system, a coastal embayment within the Town of Falmouth, Massachusetts. Analyses of the Falmouth Inner 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 Falmouth Inner 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 Falmouth Inner 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 Falmouth Inner 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 Falmouth Inner Harbor system, specifically the Waquoit Bay embayment system. In this manner, this analysis of the Falmouth Inner 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, Quissett 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 greatest assets of the Linked Model Approach 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 Falmouth Inner Harbor embayment system by using site-specific data collected by the MEP and water quality data from the volunteer efforts of scientists and graduate researchers within the Coastal Systems Program-SMAST. CSP staff and students undertook the collection of the necessary minimum three years baseline data in order to support entry of Falmouth Inner Harbor into the MEP. These "research volunteers" at CSP-SMAST initiated data collection in summer 2006 and created a 4 year baseline of summer water quality for the Harbor (2006-2009). Evaluation of upland nitrogen loading was conducted by the MEP, data were provided by the Town of Falmouth Planning Department, and watershed boundaries delineated by USGS. These land-use data were used to determine watershed nitrogen loads within the Falmouth Inner Harbor embayment system and its sub-embayments as appropriate (current and build-out loads are summarized in Table IV-3). Water quality within an 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 Falmouth Inner 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 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. Boundary nutrient concentrations in Vineyard Sound source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Falmouth Inner Harbor embayment system were 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 embayment.

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 (SB for Falmouth Inner Harbor). 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 infaunal habitats (no documented historical eelgrass) in the Falmouth Inner 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 station chosen for the Falmouth Inner Harbor system. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Falmouth Inner 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 74% - 82% of the controllable watershed load to the Falmouth Inner 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 Falmouth Inner Harbor embayment system based upon available water quality monitoring data, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure (changes in eelgrass distribution could not be used as a metric due to lack of historical eelgrass presence). At present, the Falmouth Inner 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 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 (inner and outer) of this system is manifested by the temporal changes in dissolved oxygen/chlorophyll-*a*, macroalgae and benthic community characteristics. In Falmouth Inner Harbor, all these measures of habitat health/impairment are consistent with the observed levels of nitrogen and organic matter enrichment and sediment characteristics. The distribution and levels of habitat impairment within the Falmouth Inner Harbor Embayment System is consistent with the low to moderate level of nitrogen enrichment. The lack of historical eelgrass habitat within this system makes restoration of the benthic infaunal resource the primary focus for nitrogen management.

Determining the nitrogen target to restoring water quality and the benthic habitat 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 Falmouth Inner 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 portion of the embayment. Dissolved oxygen and chlorophyll-*a* measurements supported the contention that both the inner and outer basins of Falmouth Inner Harbor are impaired by nitrogen enrichment. Both continuous records of oxygen and multi-year periodic monitoring samples indicate that the inner and outer basins of the Harbor show moderate to significant levels of oxygen depletion consistent with the nitrogen enriched conditions of harbor waters. Oxygen conditions within the inner basin exhibited large daily excursions in oxygen levels ranging from oxygen concentrations over 8 mg L^{-1} (air equilibration) to hypoxic conditions where levels declined to <4 mg L^{-1}. Within the outer basin of the harbor, oxygen concentrations generally ranged between 5 and 8 mg L^{-1} and levels periodically dropped below 5 mg L^{-1} and sometimes to <4 mg L^{-1}. Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress.

The infauna survey was consistent with the levels of oxygen depletion, phytoplankton biomass, and sediment enrichment, supporting the assessment that the outer and inner portions of Falmouth Inner Harbor are presently supporting moderately to significantly impaired benthic infaunal habitat. It appears that organic deposition in these areas is the cause of the stress. There also appears to be possible disturbance effects in concert with nutrient related stresses in the outer basin, likely due to harbor or dredging activities. Animal communities colonizing sediments within both the outer and inner basins are moderately diverse (15 and 19 species, respectively) and productive (>400 individuals per sample). Both basins ranked similarly based upon the key community indices, the Weiner Diversity Index (H') with values of 2.6 and 2.7, respectively and Evenness with values of 0.67 and 0.65, respectively. Based only upon the number of species and individuals and the community diversity and Evenness metrics, these communities would be classified as moderately impaired. When the species dominating the communities are considered, it appears that there is additional impairment in the outer basin. The inner basin benthic animal communities are dominated by species indicative of a moderate level of organic matter enrichment (amphipods, spionids). Comparison of the benthic animal communities within the inner and outer basins of Falmouth Inner Harbor to nearby high quality environments, such as the Outer Basin of Quissett Harbor, underscores the assessment of moderately to significantly impaired benthic habitat in this system. The Outer Basin of Quissett Harbor supports benthic animal communities with $\geq$28 species, >400 individuals with high diversity (H' $\geq$3.7) and Evenness (E $\geq$0.77).

In general, the integration of all of the metrics clearly indicates that the inner and outer basins of the Falmouth Inner Harbor System are supporting benthic animal habitat that is moderately to significantly impaired. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels (tidally averaged) within the upper reach of the Harbor presently range from 0.58 - 0.52 mg TN L^{-1}, a level generally found in associated analogous embayments: Fiddlers Cove and Rands Harbor, which average 0.56 mg TN L^{-1} and 0.57 mg TN L^{-1}, respectively, and other southeastern Massachusetts estuaries showing impairment of the benthic animal habitats.

3. Conclusions of the 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 integration of the watershed nitrogen load, the nitrogen concentration in the inflowing tidal waters (boundary condition) and dilution and flushing via tidal flows. The water column nitrogen concentration is modified by the extent of sediment regeneration and by direct atmospheric deposition.

Threshold nitrogen levels for this embayment system were developed to restore or maintain SB waters consistent with the extensive use of this water body as an active harbor supporting multiple marinas. In this system, high habitat quality was defined as supportive of diverse benthic animal communities. Dissolved oxygen and chlorophyll-*a* were also considered in the assessment.

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Town of Falmouth, Falmouth Inner Harbor embayment system was comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 74% - 82% of the controllable watershed nitrogen load to the embayment was from wastewater (septic and WWTF).

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 Fiddlers Cove, Rands Harbor, Wild Harbor, Great, Green and Bournes Pond Systems, Popponesset Bay System, and the nearby Eel Pond and 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 Falmouth Inner Harbor.

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

Falmouth Inner Harbor Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Falmouth Inner Harbor Embayment system should reflect both recent pre-degradation habitat quality and be reasonably achievable. The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout and embayment system, is to identify a sentinel location within the embayment or sub-embayment (as necessary) and second, to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality. Given the simple configuration and hydrodynamics of the Falmouth Inner Harbor Embayment System, a single nitrogen threshold location was selected for determination of estuarine response to reductions in watershed nitrogen loading and/or enhanced tidal flushing.

- Since nitrogen levels are highest in the upper reach, the Sentinel Station for Falmouth Inner Harbor was placed within the inner basin and was established as the average of the long-term monitoring stations that were placed at the upper (FIH-1) and lower (FIH-2) margin of the inner basin. The tidally averaged total nitrogen levels within the upper reach of the Harbor are presently 0.58 mg TN L-1 (FIH-1) and 0.52 mg TN L^{-1} (FIH-2). These TN levels are comparable to other estuarine basins throughout the region that show similar levels of oxygen depletion, organic enrichment and moderately impaired benthic animal habitat. Given that in numerous estuaries it has been previously determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat (e.g., Eel Pond, Parkers River, upper Bass River, upper Great Pond, upper Three Bays, as well as the 7 inner basins of Pleasant Bay), this level is deemed most appropriate for restoration of the basins comprising Falmouth Inner Harbor. It should be noted that estuaries with TN levels >0.50 mg L^{-1} (like Rands Harbor and Fiddlers Cove in Falmouth) show benthic animal impairments similar to the present condition of Falmouth Inner Harbor. Watershed management to meet the restoration threshold for benthic animal habitat is the focus of the nitrogen management threshold analysis.

It is important to note that the analysis of future nitrogen loading to the Falmouth Inner 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 Falmouth Inner 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 Falmouth 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										
Upper Harbor	0.096	0.558	2.015	--	2.573	0.219	0.780	3.572	0.59	--
Lower Harbor	0.145	0.837	3.023	--	3.860	0.219	0.753	4.832	0.53	--
Morse Culvert	0.151	0.157	0.477	0.130	0.764	--	--	0.764	0.50	--
System Total	**0.392**	**1.552**	**5.515**	**0.130**	**7.197**	**0.438**	**1.533**	**9.168**	**--**	**0.50[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 2006 – 2010 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 a point midway between water quality stations FIH-1 and FIH-2

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Falmouth Harbor estuary system, Town of Falmouth, 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						
Upper Harbor	2.573	1.888	0.219	0.629	2.736	-26.6%
Lower Harbor	3.860	2.832	0.219	0.632	3.683	-26.6%
Morse Culvert	0.764	0.764	--	--	0.764	0.0%
System Total	**7.197**	**5.484**	**0.438**	**1.261**	**7.183**	**-23.8%**

(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 the Town of Falmouth and drove for the completion of the Linked Watershed-Embayment Modeling Approach to Determine Critical Nitrogen Loading Thresholds for the Falmouth Inner Harbor Embayment System. 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 as part of its watershed management planning and for their commitment to the restoration of all of the estuaries of the Town. Significant time and attention has been dedicated to this effort by Jerry Potamis and Amy Lowell, whose support has been instrumental to completion of these reports. Equally important has been technical support by the Town Planner, Brian Currie. 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 this highly visible Falmouth estuary. We would also like to acknowledge the field support provided to the MEP by the Town of Falmouth Marine Department who gave us unrestricted use of the municipal marine facility to complete critical field tasks. The MEP Technical Team would also like to thank the Coastal Systems Program Staff and graduate students for making available their research data relevant to the nutrient related water quality of this system. Without this baseline water quality data the present analysis would not have been possible.

In addition, technical, policy and regulatory support has been freely and graciously provided by the Cape Cod Commission, most notably, Paul Niedzwiecki and Tom Cambareri and GIS support by Phil Detjens of the Cape Cod Commission. We are also thankful for the long hours in the field and laboratory spent by technical staff (Lizabeth White, Jen Benson, Michael Bartlett, and Sara Sampieri), interns and students within the Coastal Systems Program at SMAST-UMD.

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I. INTRODUCTION

The Falmouth Inner Harbor embayment system is located within the Town of Falmouth, on Cape Cod Massachusetts. The system has a southern shore bounded by water from Vineyard Sound (Figure I-1). The watershed for this embayment system is also distributed fully within the Town of Falmouth. The Falmouth Inner Harbor system is an "artificial" embayment, created by connecting Deacon's Pond to Vineyard Sound in 1907, to create a protected anchorage for boats. Over the past 100 years the basin has been deepened by dredging and nearly continuous shoreline armoring or bulkhead construction that now forms the shoreline. However, the process of opening Deacon’s Pond to tidal flows was likely an acceleration of a natural process that has been occurring for thousands of years on the south coast of the Town of Falmouth, as rising sea level has flooded and eroded stream valleys and kettle ponds to form estuaries. Prior to its opening for navigation, the former Deacon's Pond was already being breached during significant storm events.

The basin of Deacon’s Pond, still seen in the gross morphology of Falmouth Inner Harbor, resulted from the same processes that formed all the great salt ponds on the Falmouth portion of the southern shore of Cape Cod (e.g. Oyster Pond, Salt Pond, Little Pond, Great Pond, Green Pond and Bournes Pond). The configuration of the original basin was as a valley formed primarily by post-glacial erosion by groundwater fed rivers and streams. At present, Falmouth Inner Harbor is a tidal embayment with a stream discharging to its headwaters. This situation is mirrored in almost all of the salt ponds to the east along the southern coast of Cape Cod. As is typical with other Falmouth embayments (Great, Green, and Bournes Pond) Falmouth Inner Harbor is separated from Vineyard Sound by a barrier beach, which was breached and is now artificially maintained by jetties. The beach and the inlet are generally very dynamic geomorphic features, due to the influence of littoral transport processes.

The embayment is located within a glacial outwash plain, the Mashpee Pitted Plain, consisting of material deposited after the retreat of the Cape Cod Lobe of the Laurentide Ice sheet ~18,000 years ago. The outwash material is highly permeable and varies in composition from well sorted medium sands to course pebble sands and gravels extending down to about 17 m below mean sea level (Millham and Howes, 1994). As such, direct rainwater run-off is typically rather low for these finger ponds and therefore most freshwater inflow to the estuary is via groundwater discharge or groundwater fed surface water flow (e.g. Morse Pond is a groundwater fed kettle pond). It should be noted that the small stream discharging from Morse Pond is sometimes missed as it flows through a concrete culvert for much of its length, passing under developed parts of the Town of Falmouth before discharging directly to Harbor waters (Figure I-2).

Since its opening to regular tidal exchange, Falmouth Inner Harbor has evolved into an open water embayment with a small stream discharging to its headwaters and groundwater inflows along its shoreline. Falmouth Inner Harbor presently acts as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Vineyard sound, however, the salinity characteristics of this estuary varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with Vineyard Sound. After a century of tidal exchanges, Falmouth Inner Harbor now supports marine resources (benthic invertebrate animal communities, fish and shellfish) and is presently functioning as an open water embayment and should be managed as such.

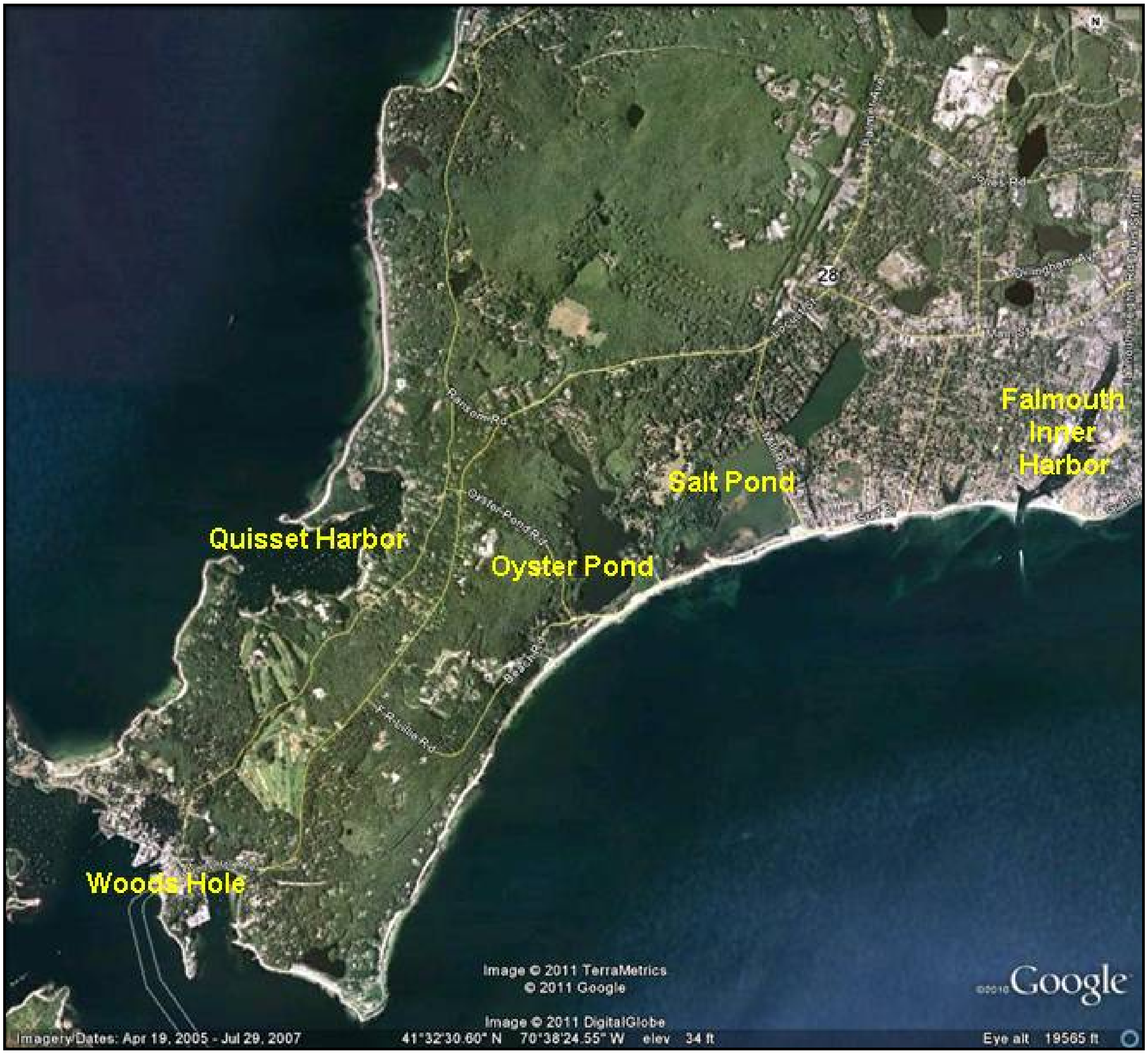

Figure I-1. Study region proximal to the Falmouth Inner Harbor embayment system for the Massachusetts Estuaries Project nutrient analysis.

Similar to the Little Pond, Great, Green and Bournes Pond embayment systems, Falmouth Inner Harbor is a nutrient enriched shallow coastal embayment. The level of nutrient enrichment and habitat quality of Falmouth Inner Harbor is linked to the level of tidal flushing through its inlet to Vineyard Sound. Although the salt pond embayment systems of Falmouth bounding Vineyard Sound exhibit slightly different hydrologic characteristics they are all tidally dominated, with tidal forcing from Vineyard Sound. Vineyard Sound, adjacent the barrier beach separating the Falmouth Inner Harbor embayment system from the ocean, exhibits a low tide range, with a mean range of about 0.5 m (1.6 ft) at the southern inlet of the harbor. Since the water elevation difference between Vineyard Sound and Falmouth Inner Harbor is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle (note the tide range off Stage Harbor Chatham is ~4.5 ft, Wellfleet Harbor is ~10 ft). The inlet is affected significantly by longshore sand transport (west to east), where shoaling can impede hydrodynamic exchange. The inlet is presently armored with jetties on the east and west side and the channel armored with riprap and features a significant navigational channel between these structures which must periodically be dredged to remove sediments transported from along the shore.

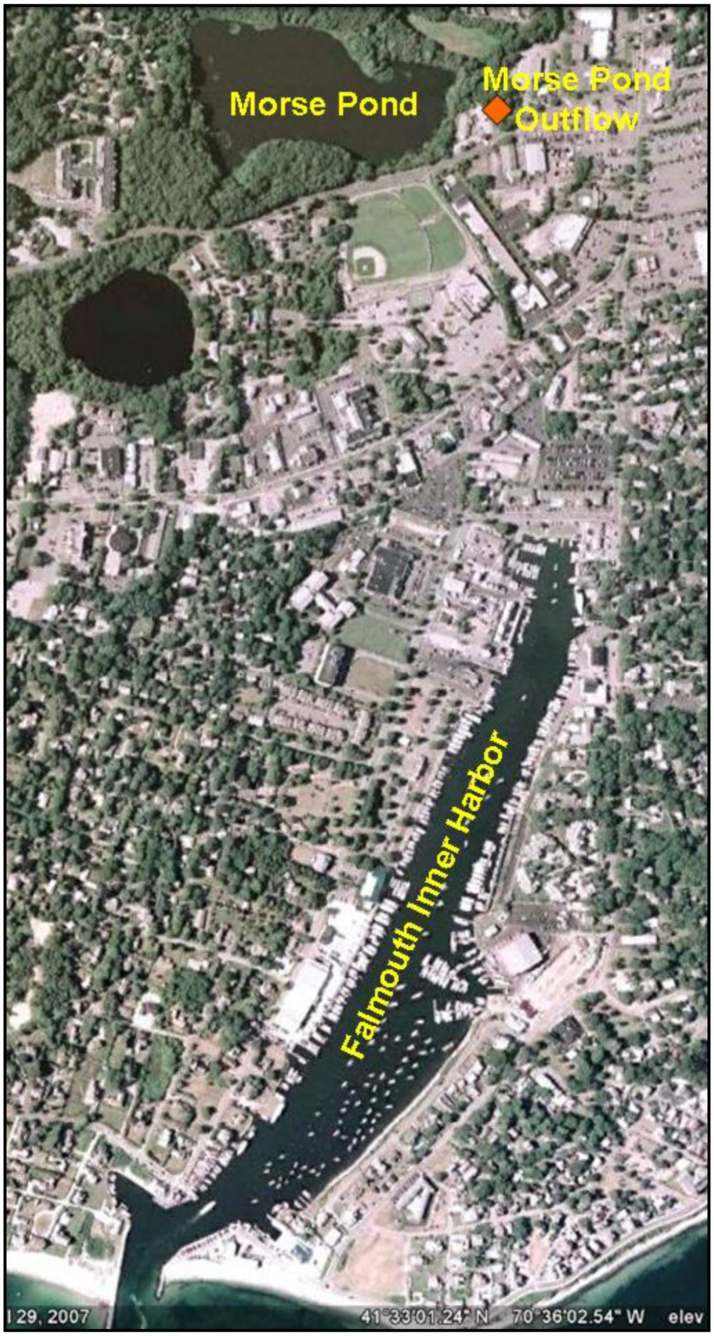

Figure I-2. Falmouth Inner Harbor depicted relative to Morse Pond (freshwater kettle pond) and stream outflow. Tidal exchange between the Harbor and Vineyard Sound is through a single stabilized inlet through the barrier beach. Freshwaters enter from the watershed primarily through direct groundwater discharge and the small stream from Morse Pond which discharges to the headwaters of the Harbor.

Falmouth Inner Harbor, along with the other salt pond embayments along the south coast of Falmouth, constitutes an important component of the Town's natural and cultural resources. In addition, the large length to width ratio (8:1) greatly increases the potential for direct discharges from development situated on the shore and decreases the travel time of groundwater from the watershed recharge areas to embayment regions of discharge. It should be noted that although there is significant commercial development in the watershed areas near the Harbor, much of the watershed presently supports residential development. The nature of enclosed embayments in populous regions brings two opposing elements to bear. As protected marine shoreline they are popular regions for boating, recreation, and land development; 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 shores. In particular, Falmouth Inner Harbor as well as Little Pond, Great, Green and Bournes Pond embayment systems along the Falmouth shoreline are at risk of eutrophication from high nitrogen loads in the groundwater and runoff from their watersheds. Unlike these other systems, Falmouth Inner Harbor is generally well flushed due to its generally small size and deep and wide inlet.

The primary ecological threat to the Falmouth Inner Harbor as an aquatic resource is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters has been greatly increased over the past few decades, although further increases will likely be small as the watershed is approaching build-out. The nitrogen loading to this and other Falmouth embayments and salt ponds, 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 two decades and does have limited centralized wastewater treatment or other significant wastewater treatment approaches within the watershed to Falmouth Inner Harbor. At present Falmouth Inner Harbor appears to be beyond its ability to tolerate additional nitrogen inputs without impairment to its marine resources. Fortunately, as the Falmouth Inner Harbor nitrogen loads are approaching their maximum for build-out under present zoning, nitrogen management options can be clearly defined and implemented with a high degree of certainty for estuarine restoration.

To this end, as the primary stakeholder to the Falmouth Inner Harbor embayment system, the Town of Falmouth was one of the first communities to become concerned over perceived degradation of embayment waters. The Town of Falmouth (via the Planning Office) has long recognized the potential threat of nutrient over-enrichment of its coastal salt ponds and embayments. In the mid-1980s 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, much like the approach of MEP and the associated TMDL process. 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 Inner Harbor in order to evaluate the effects from a nutrient enriched wastewater plume generated by the Falmouth Wastewater Treatment Facility. Water quality monitoring, however, did not extend completely to all to the estuarine systems in Falmouth and in the case of Falmouth Inner Harbor and Salt Pond, scientists and graduate student researchers from the Coastal Systems Program assumed the responsibility of collecting water samples in order to establish the minimum three year water quality baseline need for the Massachusetts Estuaries Project management modeling approach.

The Falmouth PondWatch Program, as the water quality monitoring effort came to be known, continues to play an active role in the collection of baseline water quality data to this day, though it has evolved beyond its original mandate of providing basic environmental data relative to the Coastal Pond Overlay Bylaw (Nutrient Bylaw). The Pond Watch Program brings together, as requested by Town boards, ecological information relative to specific water quality issues. Additionally, as remediation plans for various systems are implemented, the continued monitoring satisfies demands by State regulatory agencies and provides quantitative information to the Town relative to the efficacy of remediation efforts. Lastly, the PondWatch Program has grown into being a repository of environmental information on Falmouth's coastal ponds. The database includes basic water quality monitoring data in addition to special project data on watershed nutrient loading and watershed delineation, circulation characteristics of the ponds, wetland delineations and plant and animal distributions.

The common focus of the Falmouth PondWatch Program effort has been to gather site-specific data on the current nitrogen related water quality throughout Falmouth's coastal embayments (e.g. Little Pond, Great, Green, and Bournes Pond embayment systems) and determine the relationship between observed water quality and watershed nitrogen loads. This multi-year effort has provided the baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. While the PondWatch Program did not develop the baseline water quality data for Falmouth Inner Harbor, the program did develop information for other coastal ponds, elucidating the long-term trend of declining water quality and its relation to watershed based nutrient loading in a manner consistent with data collection in Falmouth Inner Harbor. The advantage of the consistent approach to water quality monitoring is the future ability to cross compare existing and future water quality conditions in the various embayments of the Town of Falmouth and relate those conditions to the implementation of nutrient management alternatives. The MEP effort builds upon the Falmouth water quality monitoring program, and previous hydrodynamic and water quality analyses, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Falmouth Inner Harbor embayment system, including any major sub-embayments, of which there are none for the Falmouth Inner Harbor system. This is unlike the adjacent Great Pond system which has Perch Pond as a sub-embayment connected to the main bay of Great Pond

Falmouth's 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. Unfortunately, PondWatch monitoring has documented that most regions within the Town's coastal ponds are currently showing water quality declines and are beyond the limits set by the By-law. Based on the wealth of information obtained over the many years of study of the coastal ponds in the Town of Falmouth, the Falmouth Inner Harbor embayment system was included in the Massachusetts Estuaries Project to provide state-of-the-art assessment and modeling to support Town of Falmouth management of this estuarine system.

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 Falmouth to develop and evaluate the most cost effective nitrogen management alternatives to restore the valuable coastal resources which are 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. 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 declining 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 use. Similar to nutrients, bacterial contamination is related to changes in land-use as watershed become more developed. Regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to 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 Management 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.

The major Project goals are to:

- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 70 out of 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment's model "alive" 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 embayment's: (1) nitrogen sensitivity, (2) nitrogen threshold loading levels (TMDL) and (3) response to changes in loading rate. The approach is fully field validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-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

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 Falmouth Inner 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 Falmouth Inner Harbor follow this general pattern, where the primary nutrient of eutrophication in this and other Falmouth embayment systems is nitrogen.

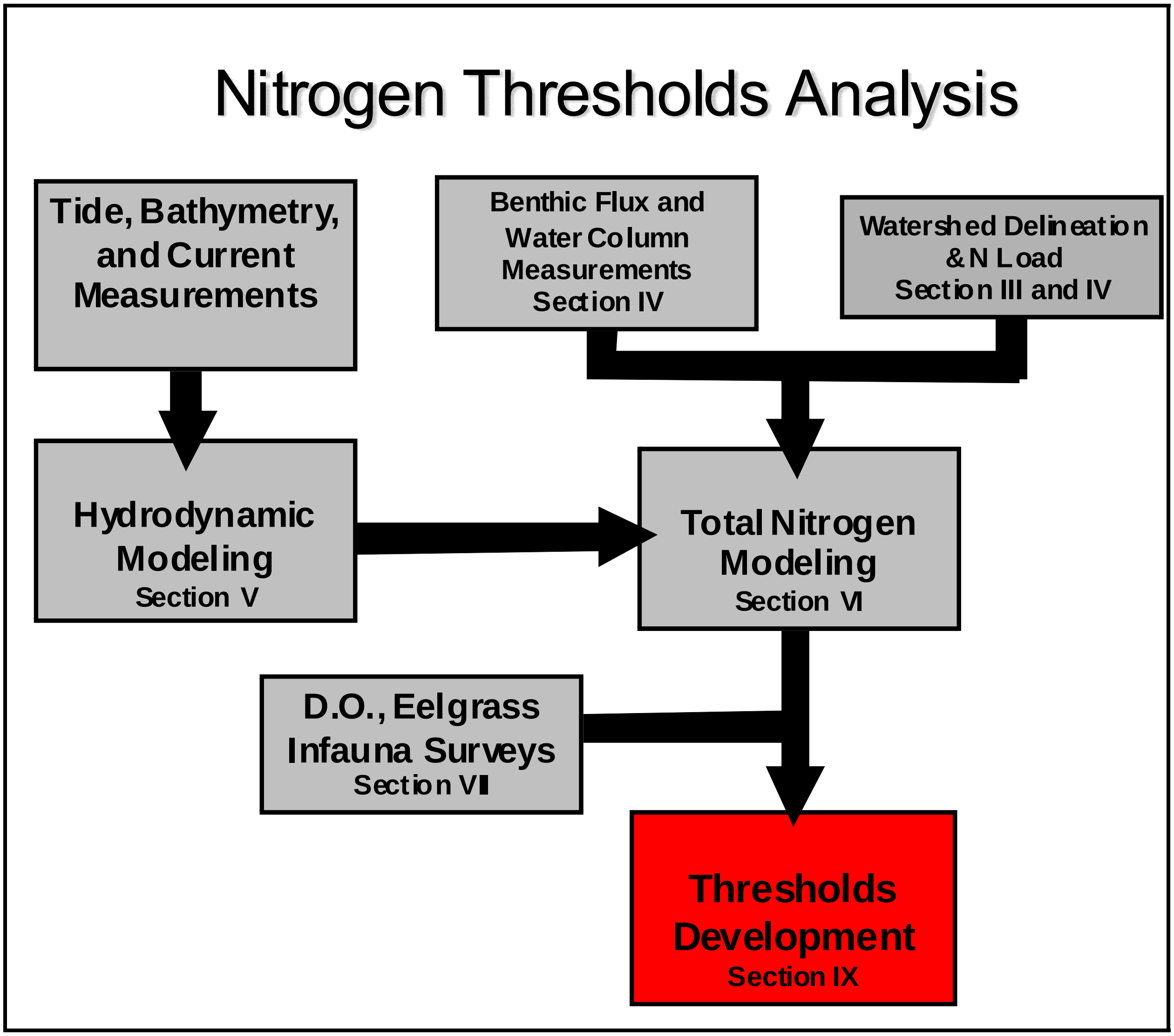

Figure I-3. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

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

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

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

Unfortunately, most all of the estuarine reach within Falmouth Inner Harbor is near or beyond its ability to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated throughout the system and benthic infaunal communities are generally indicative of impaired habitat. While the basin has been functioning as an open water embayment for over a century, eelgrass beds have not been observed within its tidal reaches. The result is that nitrogen management of the Falmouth Inner Harbor embayment is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed “eutrophication” and when the nutrient loading is primarily from human activities, “cultural eutrophication”. Although the influence of human-induced changes has increased nitrogen loading to the system and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within Falmouth Inner Harbor could potentially occur without man’s influence and must be considered in the nutrient threshold analysis. This consideration is, however, complicated by the fact that little about Falmouth Inner Harbor basins are natural given the harbor was created from what was historically a pond generally isolated from Vineyard Sound. While this finding would not change the need for restoration, it would change the approach and potential targets for management.

I.3 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” for water quality modeling of the Falmouth Inner 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 Falmouth Inner Harbor. 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 was computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations by USGS using a modification of the West Cape model for sub-watershed areas designated by MEP. Almost all nitrogen entering Falmouth's salt ponds is transported by freshwater, predominantly groundwater, either through direct discharge or after discharging to streams flowing to estuarine waters. Concentrations of total nitrogen and salinity of Vineyard Sound source waters and throughout the Falmouth Inner Harbor system was taken from the water quality monitoring efforts of staff and graduate researchers at the Coastal Systems Program at SMAST. Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of the system were used to calibrate and validate the water quality model (under existing loading conditions).

I.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Falmouth Inner Harbor 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 Vineyard Sound (Section IV). 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 undertaken by SMAST) 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 the Falmouth Inner Harbor 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 salt pond. 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 the Falmouth Inner Harbor system.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

Nutrient additions to aquatic systems cause shifts in a series of biological processes that can result in impaired nutrient related habitat quality. Effects include excessive plankton and macrophyte growth, which in turn lead to reduced water clarity, organic matter enrichment of waters and sediments 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 dependant 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 a necessarily a part of the natural evolution of a system.

In most marine and estuarine systems, such as the Falmouth Inner Harbor System, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then habitat impairments resulting from eutrophication are 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. 2003).

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 for the specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Falmouth Inner Harbor System. As the MEP approach requires substantial amounts of site-specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of “data mining” and to gather additional information on an estuary’s habitat quality and unique features.

In the case of Falmouth Inner Harbor, few studies relating to environmental contamination and habitat health have been conducted over the past three decades to inform the MEP habitat assessment and threshold development process. Available studies that were integrated into the present Massachusetts Estuaries Project effort to develop a nitrogen threshold for Falmouth Inner Harbor are summarized below.

Falmouth Inner Harbor Nutrient Related Water Quality Monitoring: The MEP analysis requires high quality water quality data in order to complete its assessment and modeling approach. Water quality monitoring in the Town of Falmouth's estuaries has been a multi-faceted program generally based on technical support from the Coastal System Program-SMAST, providing consistency of results. Water quality monitoring across all of the embayments in the Town of Falmouth has been completed over the years through four main groups depending on the embayment system: 1) Coalition for Buzzards Bay for Buzzards Bay systems, 2) the Falmouth PondWatch for south coast estuaries 3) the Coastal Systems Program-SMAST for south shore systems not monitored by PondWatch and 4) Water Quality Monitoring Collaborative (Mashpee Wampanoag Tribe, Town of Mashpee, CSP-SMAST) for Waquoit Bay and Eel Pond.

The Coalition for Buzzards Bay’s Water Quality Monitoring Program has been collecting data on nutrient related water quality throughout Buzzards Bay estuaries for more than a decade, inclusive of Quissett Harbor, Wild Harbor, outer Megansett Harbor, Fiddlers Cove and Rands Harbor in the Town of Falmouth. The Coalition’s BayWatcher Program has collected the principal baseline water quality data to support ecological management of each of Falmouth’s Buzzards Bay embayments. The BayWatchers is a citizen-based water quality monitoring program coordinated by T. Williams with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD through 2008. The program has a USEPA and MassDEP approved Quality Assurance Project Plan (QAPP).

The Town of Falmouth implemented a water quality monitoring program to collect baseline water quality data in specific south shore systems in the town in collaboration with researchers now at the Coastal Systems Program at SMAST. The Town of Falmouth has long recognized the potential threat of nutrient over-enrichment of its coastal salt ponds and embayments. In the mid-1980s the Town enacted an innovative Nutrient Overlay By-law that tied watershed development to water quality within the adjacent embayment. The goal was to keep nitrogen concentrations in the receiving systems below thresholds that were projected to cause water quality shifts. The water quality monitoring program, Falmouth PondWatch, was established to provide on-going nutrient related embayment health information in support of the By-law. The first three Ponds to undergo water quality monitoring in the Town of Falmouth were Oyster Pond, Little Pond and Green Pond. These approaches were primarily initiated for planning as development within coastal watersheds progressed. The Town of Falmouth Planning Department has continued to enhance its tools for gauging future nutrient effects from changing land-uses. The GIS database used in the present study is part of that continuing effort. Unfortunately, monitoring has documented that most regions within the Town’s coastal ponds are currently showing water quality declines and are beyond the limits set by the By-law.

Over time the PondWatch Water Quality Monitoring Program expanded to also collect water quality data from Great Pond, Bourne’s Pond and West Falmouth Harbor. Because of these efforts, all PondWatch estuaries have completed Massachusetts Estuaries Project assessments and also have USEPA accepted TMDL's to support the Town of Falmouth's on-going restoration efforts. However, PondWatch did not include monitoring of Salt Pond or Falmouth Inner Harbor, Eel Pond or Waquoit Bay. Faced with the lack of necessary water quality baseline data for Falmouth Inner Harbor to conduct the Massachusetts Estuaries Project's assessment, the scientists and graduate researchers within the Coastal Systems Program-SMAST undertook the collection of the necessary minimum three years baseline data in order to support entry of Falmouth Inner Harbor into the MEP. These "research volunteers" at CSP-SMAST initiated data collection in summer 2006 and created a 4 year baseline of summer water quality for the Harbor (2006-2009). The water quality data collected in Falmouth Inner Harbor was collected using the same protocols developed and implemented for the collection of water quality data by the other 3 groups monitoring the other estuaries in the Town of Falmouth. In this manner all water quality data collected from all the embayments in the Town of Falmouth would be consistent and cross comparable.

The common focus of all 4 water quality monitoring efforts has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments of the Town of Falmouth to support evaluations of observed water quality and habitat health. The CSP-SMAST effort in the Falmouth Inner Harbor Embayment System developed the only water quality baseline for this system (Figure II-1). Samples were analyzed at 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. The baseline water quality data were a prerequisite to entry into the MEP. Implementation of the MEP’s Linked Watershed-Embayment Approach necessarily incorporates the quantitative water column nitrogen data (2006-2009) gathered by the Monitoring Program and watershed and embayment data collected by MEP staff.

Since the results of the baseline Water Quality Monitoring Program (2006-2009) and initial habitat assessments suggest that that portions of the Falmouth Inner Harbor Embayment System is presently beyond its ability to assimilate nitrogen without impairment to key estuarine habitats, 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 Falmouth Inner Harbor and to develop nutrient thresholds to guide the Town's estuarine management planning relative to its restoration.

Regulatory Assessments of Falmouth Inner Harbor Resources - In addition to locally generated studies of Falmouth Inner Harbor are part of the Commonwealth's environmental surveys to support regulatory needs. The Falmouth Inner Harbor Estuaries contain a variety of marine 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 natural resources. The MEP also gathers the available information on these resources as part of its assessment, and presents some of them here for reference by those providing stewardship for this estuary and some in Section VII to support the nitrogen thresholds analysis. For the Falmouth Inner 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)

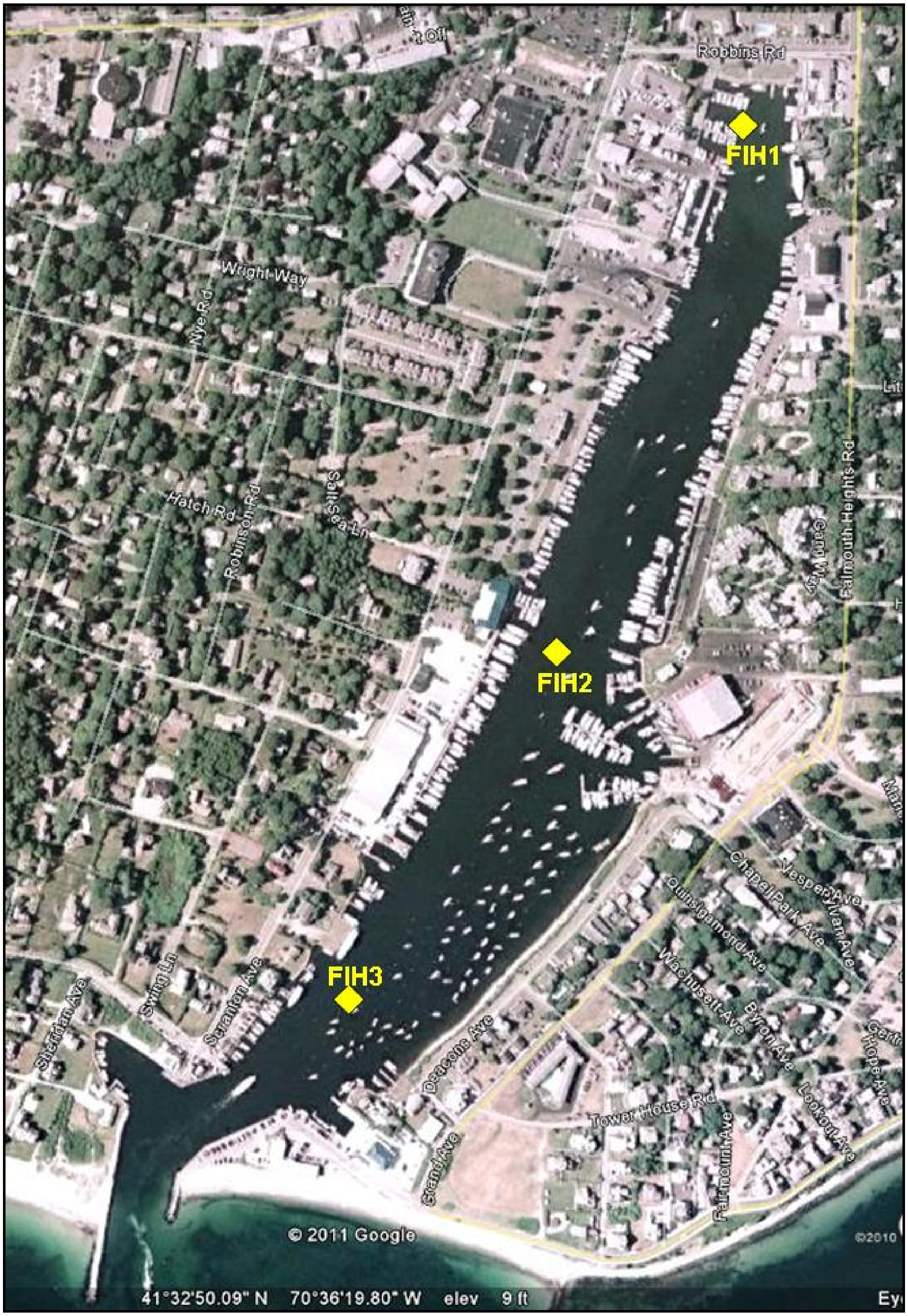

Figure II-1. Coastal Systems Program-SMAST Water Quality Monitoring Program for Falmouth Inner Harbor. Estuarine water quality monitoring stations sampled by the CSP and analyzed at the CSP-SMAST analytical facility during summers 2006 to 2009.

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 to develop thresholds for nitrogen management planning for the Falmouth Inner Harbor Embayment System. The MEP has incorporated appropriate and available data from pertinent previous and on-going studies to enhance the determination of nitrogen thresholds for the Falmouth Inner Harbor System and to reduce costs to the Town of Falmouth.

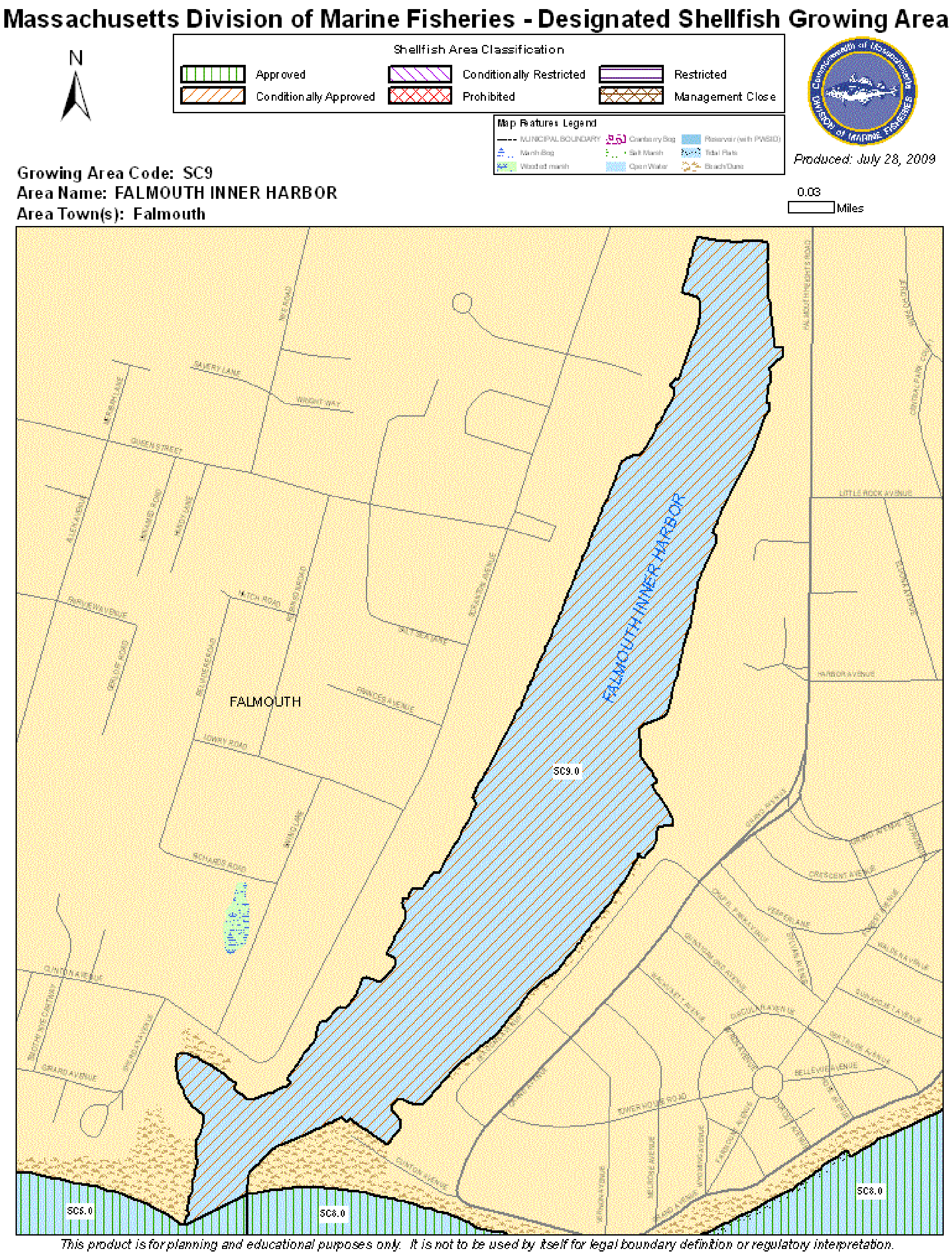

Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or the presence of "activities", such as the location of marinas.

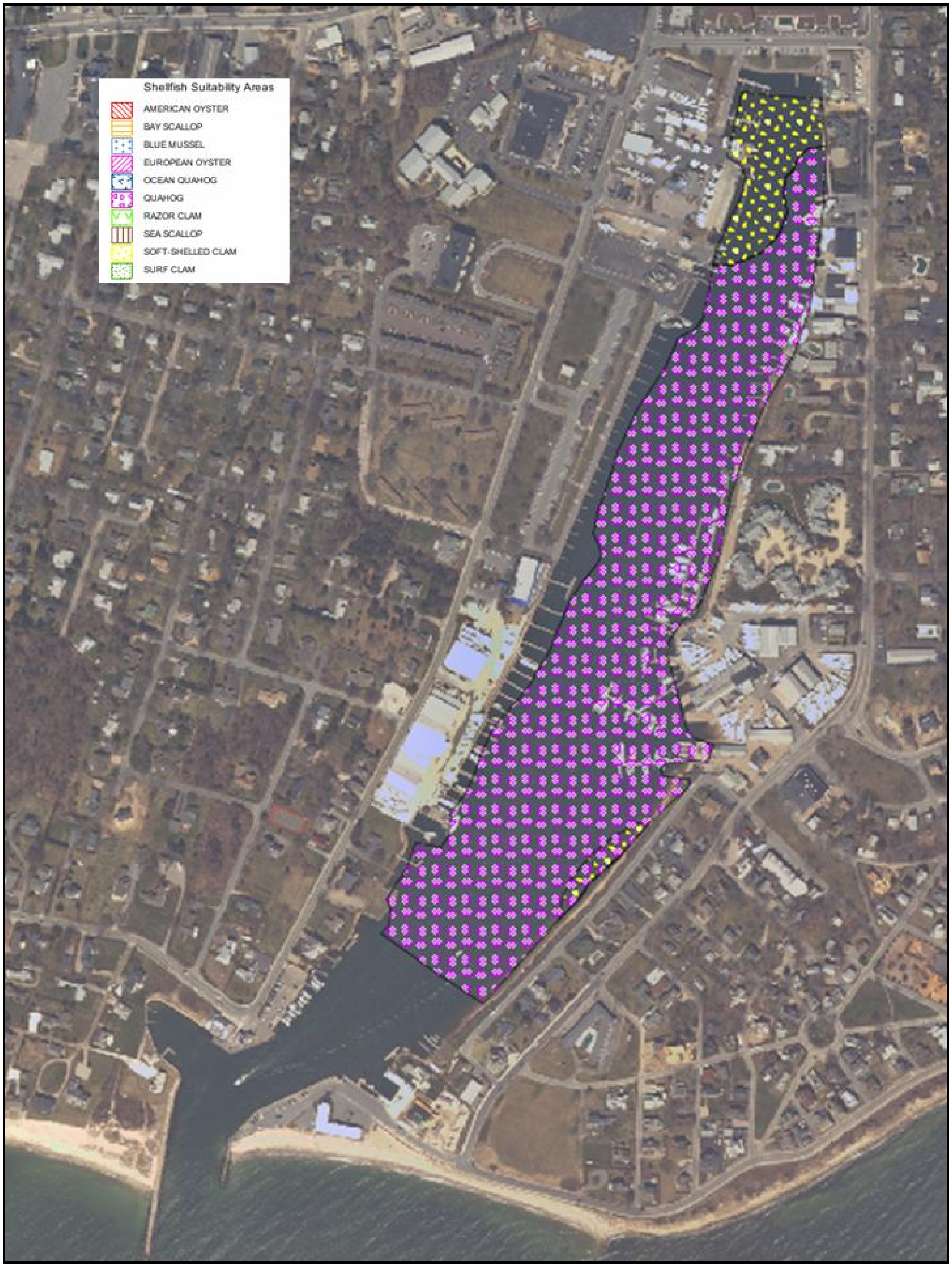

Figure II-3. Location of shellfish suitability areas within the Falmouth Inner Harbor Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

Figure II-4. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Falmouth Inner 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 Falmouth Inner Harbor embayment system. The Falmouth Inner Harbor embayment and its watershed are located entirely within the Town of Falmouth.

In the present assessment, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the Falmouth Inner Harbor embayment system under evaluation by the Project Team. The Falmouth Inner Harbor estuarine system is presently functioning as an open water embayment, tributary to Vineyard Sound, since its conversion to a tidal estuary in 1907 by the dredging of a channel into a fresh pond, Deacon's Pond. Watershed modeling was undertaken to sub-divide the overall watershed to the Falmouth Inner Harbor system into functional sub-units based upon: (a) defining inputs from contributing areas to each major component of the embayment system, (b) defining contributing areas to major freshwater aquatic systems which attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands), and (c) defining the land areas with groundwater travel times that are greater and less than 10 years time-of-travel to the estuary. These time-of-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. The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in both the Sagamore and Monomoy flow cells on Cape Cod; the Falmouth Inner Harbor watershed is located along the western edge of the Sagamore flow cell. Model assumptions for calibration of the Falmouth Inner Harbor Estuary included surface water discharges measured as part of the MEP stream flow program (2006 to 2007).

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 to estuarine waters via groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Falmouth Inner Harbor system and its various sub-watersheds, such as Morse and Jones Ponds, were delineated using the regional model of the Sagamore Lens flow cell (Walter and Whealan, 2005). 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 Falmouth Inner Harbor system and its sub-watersheds and also to determine portions of recharged water that may flow through fresh water ponds and streams prior to discharging into coastal water bodies.

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). In most of the Falmouth Inner Harbor watershed area, bedrock is approximately 200 feet below NGVD 29, so the lowest model layer was inactive in this area of the model with variable thickness in the layer directly above. Near the inlet of the Harbor, bedrock drops away, so the southern part of the watershed has the lowest layer of the model as an active layer. 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 sediments generally show a fining downward with sand and gravel deposits deposited in glaciofluvial (river) and near-shore glaciolacustrine (lake) environments underlain by fine sand, silt and clay deposited in deeper, lower-energy glaciolacustrine environments. Most groundwater flow in the aquifer occurs in shallower portions of the aquifer dominated by coarser-grained sand and gravel deposits. Falmouth Inner Harbor is situated on the westernmost edge of the very-coarse grained Mashpee Pitted Plain deposits (Masterson, et al., 1996). 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. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Towns and water level and streamflow 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 FALMOUTH INNER HARBOR SYSTEM CONTRIBUTORY AREAS

The refined watershed and sub-watershed boundaries for the Falmouth Inner Harbor embayment system, including Morse and Jones Ponds (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 pond and coastal shorelines, (c) to include water table data in the lower regions of the watersheds near the coast (as available), (d) to more closely match the sub-estuary segmentation of the tidal hydrodynamic model and (e) to address streamflow measurements collected as part of the MEP. The smoothing refinement was a collaborative effort between the USGS and the rest of the MEP Technical Team. The MEP sub-watershed delineation includes 10-yr time-of-travel boundaries. Overall, four (4) sub-watershed areas, were delineated within the Falmouth Inner Harbor study area.

Table III-1 provides the daily freshwater discharge volumes for various sub-watersheds as calculated from the groundwater model; these volumes were used in the salinity calibration of the tidal hydrodynamic model and to determine hydrologic turnover in the lakes/ponds, as well as for comparison to the directly measured surface water discharges. The overall estimated freshwater flow into the Falmouth Inner Harbor system from the MEP delineated watershed is 3,087 m3/d. This flow includes corrections for outflow from Jones Pond, which straddles the boundary of the Falmouth Inner Harbor watershed and the Little Pond watershed (Howes, *et al.*, 2006).

The MEP watershed delineation is the second watershed delineation completed in recent years for the Falmouth Inner 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 developed 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 Falmouth Inner Harbor System as a whole is 17% smaller than 1998 CCC delineation (495 acres vs. 578 acres, respectively). This difference is largely due to a refinement in flow paths from inland to the coast. The outer boundary of the MEP and CCC watersheds are generally coincident near the Inner Harbor with the major differences in the northern portion of the watershed; the CCC watershed extending further to the north and bending west to the regional groundwater divide. The MEP watershed generally follows north/south flow paths. The MEP watershed delineation also includes interior sub-watersheds to various components of the Falmouth Inner Harbor system, such as ponds and streams that were not included in the CCC delineation. The inner subwatershed delineations show the connections between adjacent watersheds and the complexities of flow paths. These refinements are another benefit of the update of the regional groundwater model (Walter and Whealan, 2005).

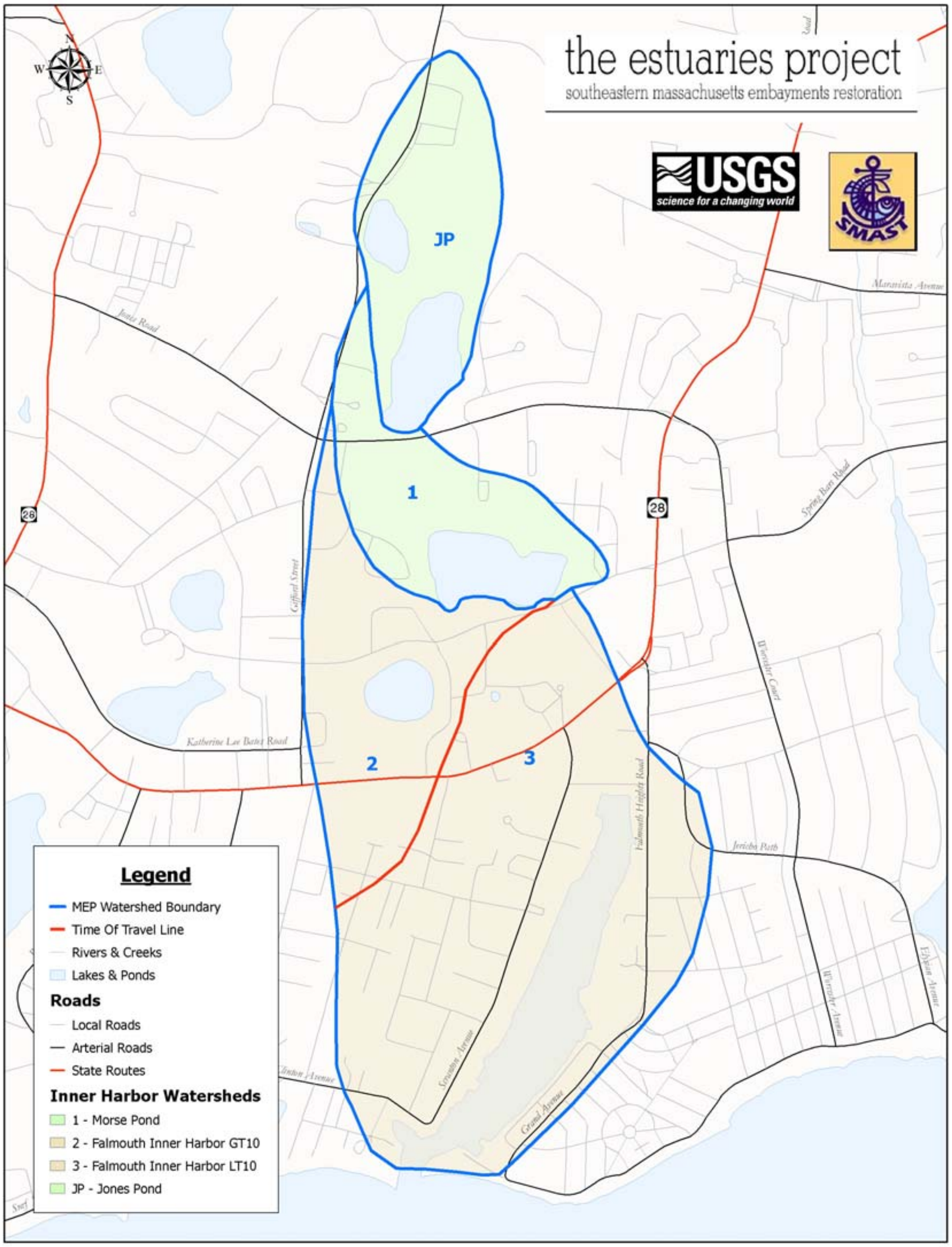

Figure III-1. Watershed and sub-watershed delineations for the Falmouth Inner Harbor System. Delineations are based on USGS groundwater model output with refinements to better address pond and estuary shorelines and MEP stream gauge measurements. Ten-year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names. Jones Pond watershed (JP) is shared with the Little Pond MEP watershed (Howes, *et al*., 2006). Note that almost all of the Falmouth Inner Harbor watershed is within 10 years groundwater travel to the estuary.

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

Watershed	#	Watershed Area (acres)	% contributing to Estuaries	Discharge	
				m^3/day	ft^3/day
Morse Pond	1	64	100%	494	17,432
Falmouth Inner Harbor GT10	2	83	100%	637	22,502
Falmouth Inner Harbor LT10	3	206	100%	1,579	55,752
Jones Pond	JP	147	72%	377	13,315
TOTAL FALMOUTH INNER HARBOR SYSTEM				3,087	109,002

Notes: 1) discharge volumes are based on 27.25 inches of annual recharge on adjusted watershed areas (total watershed areas are shown); 2) Jones Pond is shared with Little Pond watershed (Howes, *et al*., 2006), percentage of flow from Jones Pond is determined by length of downgradient watershed boundary, 3) these flows do not include precipitation on the surface of the estuary, 4) totals may not match due to rounding.

The evolution of the watershed delineations for the Falmouth Inner 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 and strengthens the model for the use of this model in 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 aquatic systems and ultimately to the estuarine waters of the Falmouth Inner Harbor system (Section V.1).

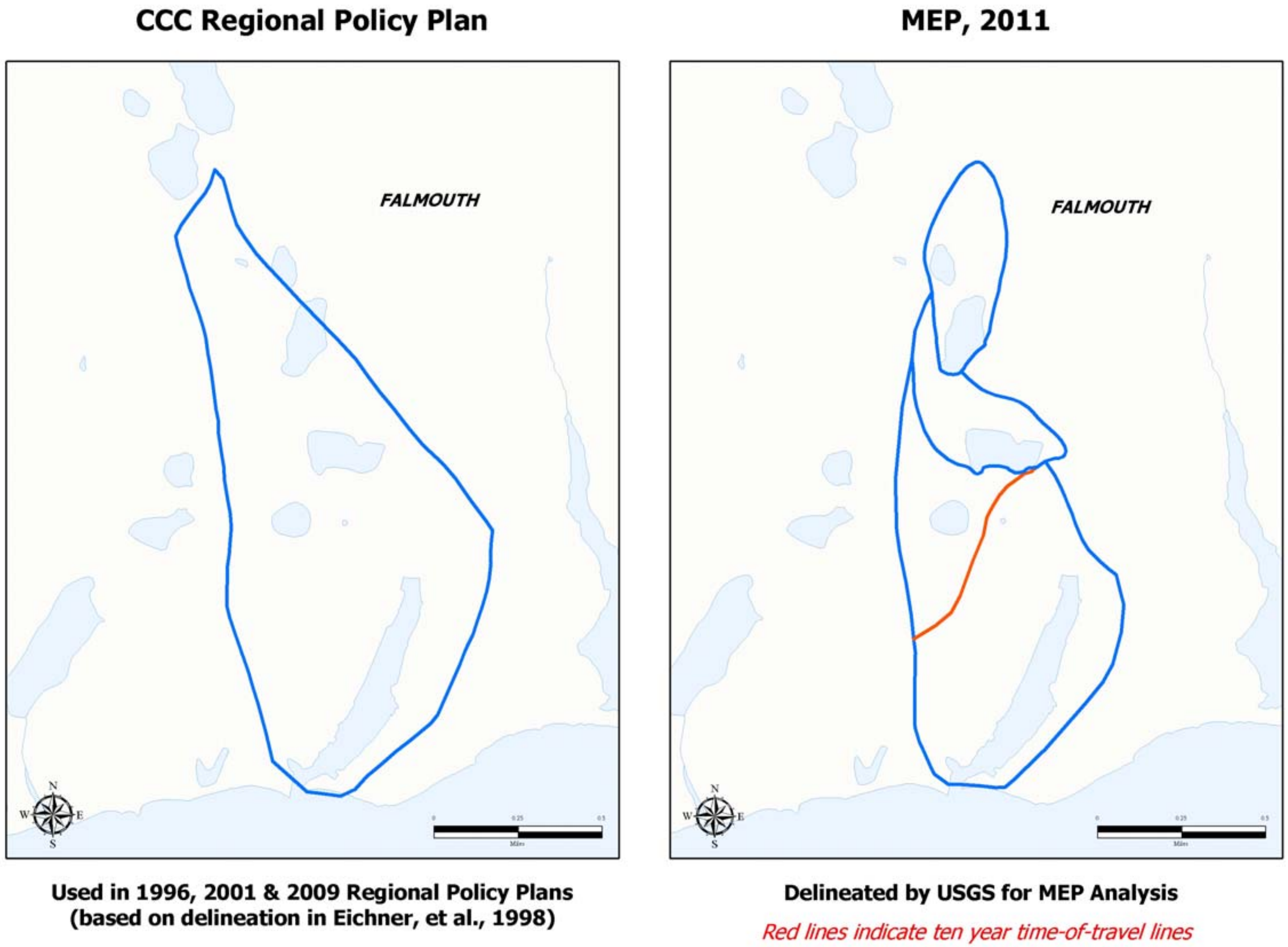

Figure III-2. Comparison of the MEP Falmouth Inner Harbor watershed and sub-watershed delineations used in the current assessment and the Cape Cod Commission watershed delineation (Eichner, *et al*., 1998) used in three Barnstable County Regional Policy Plans (CCC, 1996, 2001, 2009). The MEP watershed area for the Falmouth Inner Harbor system as a whole is 17% smaller than 1998 CCC delineation.

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 also true for the Falmouth Inner 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 Falmouth Inner Harbor estuary system, the MEP Technical Team developed nitrogen-loading rates (Section IV.1) to each component of the estuary and its watersheds (Section III). The Falmouth Inner Harbor watershed was sub-divided to define contributing areas or sub-watersheds to each of the major inland freshwater systems and to each major portion of the estuary. Further sub-divisions were made to identify watershed areas where a nitrogen discharge reaches estuary waters in less than 10 years or greater than 10 years. A total of four (4) sub-watersheds were delineated in the overall Falmouth Inner Harbor watershed, including watersheds to Morse and Jones Ponds. Jones Pond is shared with the Little Pond estuary system (Howes, et al., 2006). The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and 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. Ten-year time of travel sub-watersheds in the Falmouth Inner Harbor watershed have been delineated for ponds, streams and the estuary itself. Simple review of less than and greater than watersheds indicates that 57% of the unattenuated nitrogen load from the whole watershed is within less than 10 year travel time to the estuary (Table IV-1). The system is more complicated, however, because Morse Pond, which is on the 10 year time-of-travel boundary, has a direct stream connection to the harbor. This direct connection means that the nitrogen load that reaches Morse Pond, all of which occurs within 10 years including the load from Jones Pond, is held in the pond for its residence time then flows into the Harbor, all within 10 years. If Morse Pond is added to the less than 10-yr time-of-travel category, then 82% of the unattenuated load is within less than 10 year travel time to the estuary. If this review is further refined by adding in loads from precipitation on the estuary surface, the percentage that reaches the estuary within 10 years increases to 87%. 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 (after accounting for natural attenuation, see below) and that the distinction between time of travel in the sub-watersheds is not important for modeling existing conditions. Overall and based on the review of all this information, it was determined that the Falmouth Inner 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 Falmouth Inner Harbor.

WATERSHED		LT10	GT10	TOTAL	%LT10
Name	#	kg/yr	kg/yr	kg/yr	
Morse Pond	1	848		848	100%
Falmouth Inner Harbor GT10	2		594	594	0%
Falmouth Inner Harbor LT10	3	1,737		1,737	100%
Jones Pond	JP	166		166	100%
Falmouth Inner Harbor Whole System		2,751	594	3,345	82%

Notes: 1) these loads include a correction for the stream connection of Morse Pond to the Inner Harbor, this connection shortens the travel time for nitrogen from Morse and Jones Ponds to less than 10 years; 2) addition of loads from precipitation on the estuary surface increases the percentage of watershed nitrogen load within 10-year time-of-travel to estuary increases to 87%

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 Falmouth Inner 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 alternative septic system monitoring). 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.

Natural attenuation of nitrogen during transport from land-to-sea within the Falmouth Inner Harbor watershed was determined based upon a site-specific study of streamflow and theoretical and measured attenuation in the up-gradient freshwater ponds. Streamflow was characterized at the stream outlet from Morse Pond. The land-use analysis within the sub-watershed to the pond allows comparison between field collected data from the stream monitoring and estimates from the nitrogen-loading sub-model. Nitrogen attenuation in individual ponds is generally limited by the amount and quality of available information. Attenuation through freshwater ponds is conservatively assumed to equal 50% unless there is sufficient reliable monitoring and pond physical data to calculate a pond-specific nitrogen attenuation factor. Attenuation by freshwater systems up-gradient of the stream discharge to the headwaters of Falmouth Inner Harbor and the measured freshwater flow and associated nitrogen load is presented in Section IV.2, below.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to affect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. In the present effort, two freshwater ponds have delineated sub-watersheds within the Falmouth Inner Harbor watershed: Morse Pond and Jones Pond. 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 without flowing through one of these interim pond and stream measuring points. Internal nitrogen recycling was also determined throughout the tidal reaches of the Falmouth Inner Harbor Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

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

Figure IV-1 shows the land uses within the watershed to the Falmouth Inner Harbor estuary. Land uses in the study area are grouped into six (6) land use categories: 1) residential, 2) commercial, 3) mixed use, 4) undeveloped, 5) public service/government, including road rights-of-way, and 6) 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. Unclassified parcels are properties without any assessor land use classifications.

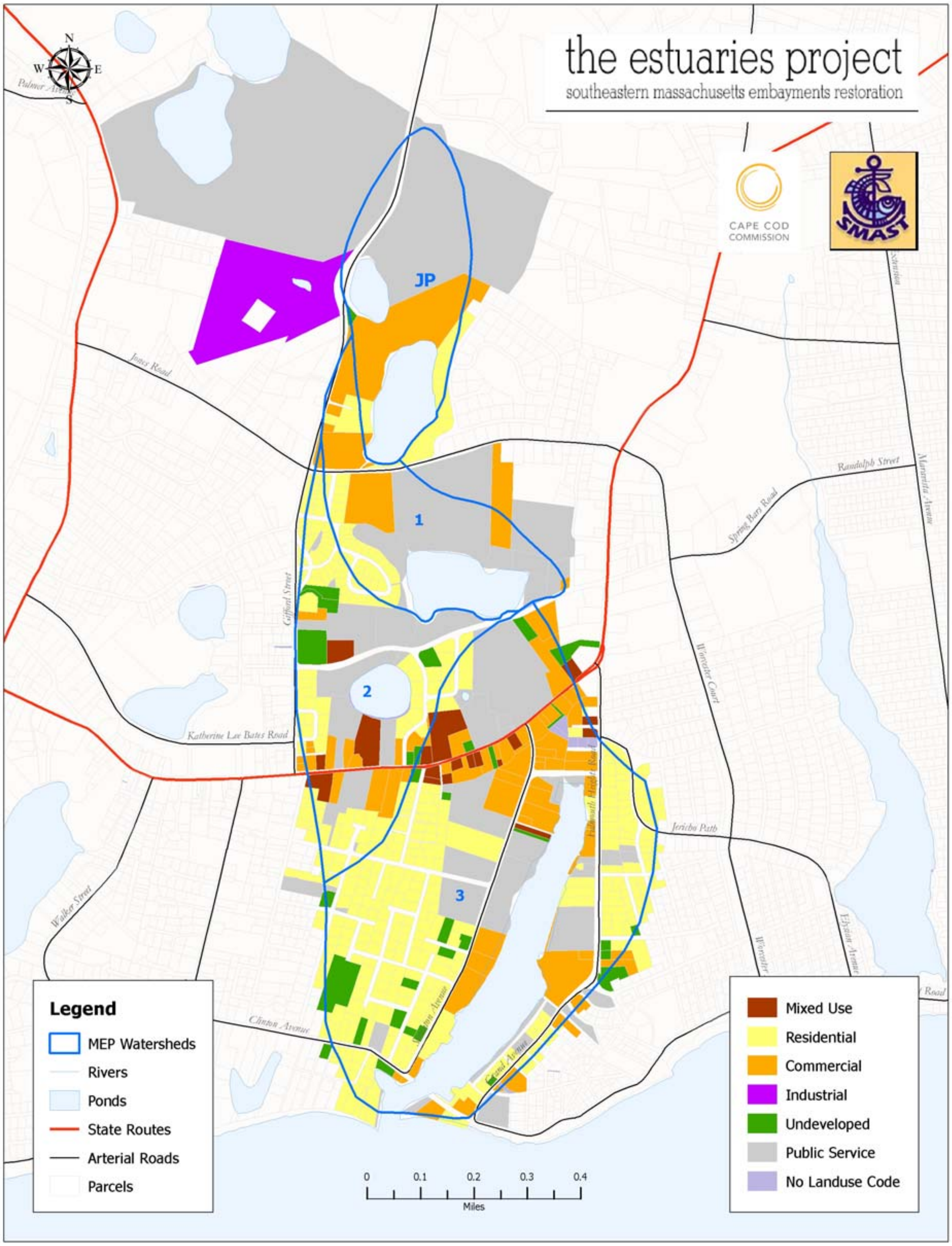

Figure IV-1. Land-use in the Falmouth Inner Harbor system watershed and sub-watersheds. The system watershed is wholly contained within the Town of Falmouth. Land use categories that are shown are based on town assessor classifications and MADOR (2009) general groupings. Base assessor and parcel data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

Public service land uses are the dominant land use type in the overall Falmouth Inner Harbor watershed and occupy 39% of the overall watershed area (Figure IV-2). These land uses are also the dominant land use type in all but one of the sub-watersheds shown in Figure IV-2; residential land uses are the dominant land use type in the Falmouth Inner Harbor LT10 sub-watershed. Freshwater area is the second largest land use type in two of the pond sub-watersheds with commercial land use types as the third largest. Examples of public service land uses are lands owned by town and state government (including open space), housing authorities, and churches. It is notable that land classified by the town assessor as undeveloped is 4% of the overall watershed area.

In all the sub-watersheds shown in Figure IV-2 and the overall Falmouth Inner Harbor watershed, residential parcels are the dominant parcel type, ranging between 66% and 73% of all parcels in these sub-watersheds and 68% of all parcels in the system watershed. Single-family residences (MassDOR land use code 101) are the dominant type of residential parcel; these represent 84% to 94% of residential parcels in the individual sub-watershed groupings and 88% of the residential parcels throughout the Falmouth Inner Harbor system watershed.
In order to estimate wastewater flows within the Falmouth Inner Harbor study area, MEP staff also obtained parcel-by-parcel water use data from the Town of Falmouth (personal communication, Bob Shea, GIS Coordinator, 11/2010). Three years of water use (fiscal years 2008, 2009 and 2010 was obtained from the town. The water use data were linked to the respective town parcel databases by the town 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 Town also provided GIS coverage of parcels connected to the town sewer system. These parcels were identified and their water use and potential wastewater nitrogen load was removed from the watershed; there are 66 parcels in the watershed that are connected to the municipal sewer system. The final wastewater nitrogen load for each parcel is based upon the measured water-use, the MEP wastewater loading factor (which is a combination of nitrogen concentration and consumptive use), and whether the parcel is connected to the town sewer system. Any developed parcels not connected to the sewer system are assumed to utilize on-site septic systems for wastewater treatment; wastewater nitrogen loads from these properties are included in the watershed nitrogen loading model.

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}.

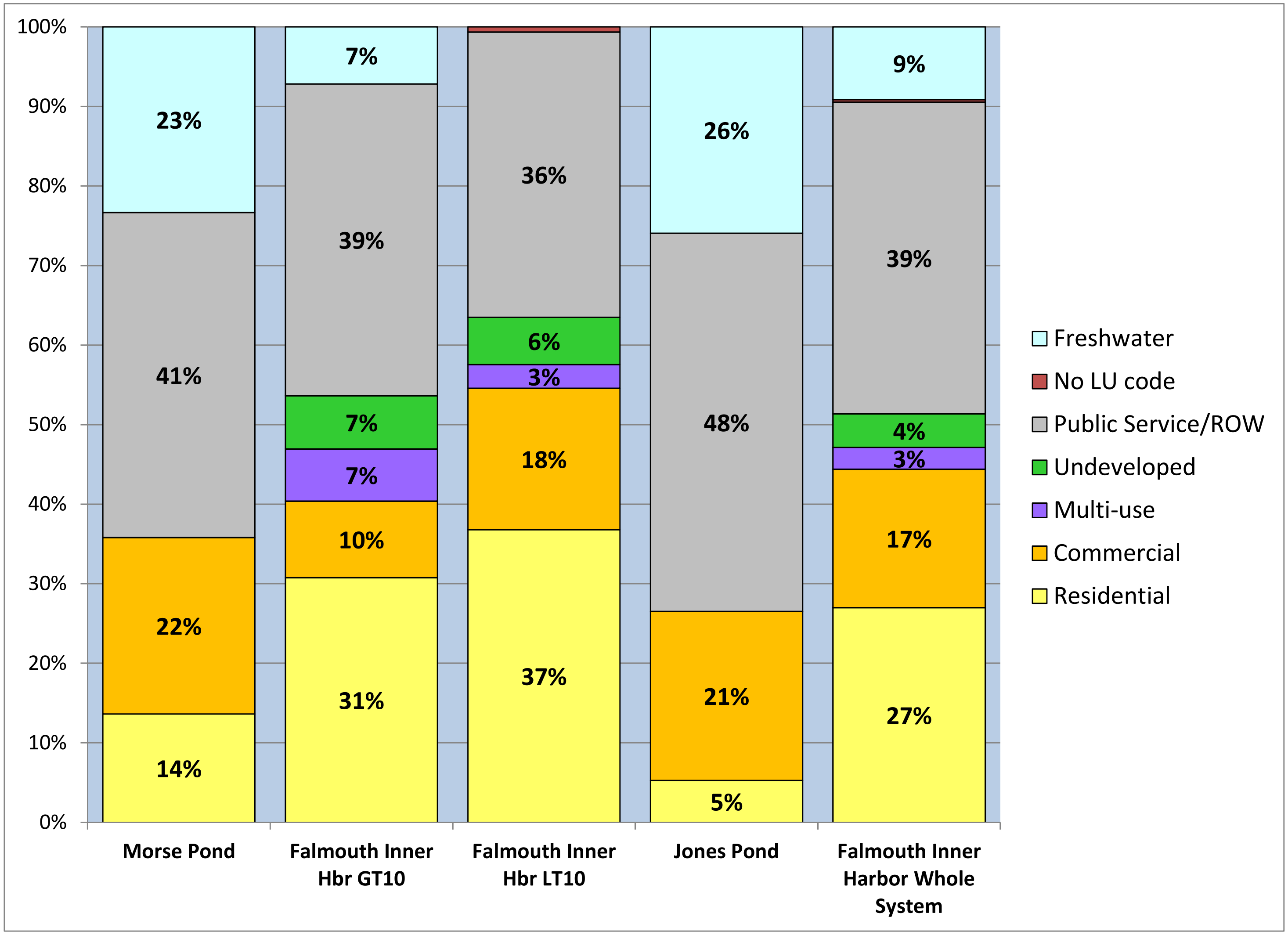

Figure IV-2. Distribution of land-uses by area within the Falmouth Inner Harbor System watershed and four component sub-watersheds. Land use categories are generally based on town assessor's land use classification and groupings used by MADOR (2009). Parcels without land use codes do not have an assigned land use codes in the town assessor's databases. Only percentages greater than or equal to 3% are labeled.

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 use 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 corrected 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 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 Falmouth Inner Harbor watersheds, MEP staff reviewed US Census population values for the Town of Falmouth. 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. Based on data collected during the 2000 US Census, average occupancy within Falmouth is 2.36 people per housing unit with 69% year-round occupancy, while 2010 Census information indicates that the average occupancy dropped to 2.24 people per housing unit and the year-round occupancy also dropped to 64%. Average water use for single-family residences with municipal water accounts in the Falmouth Inner Harbor MEP study area is 122 gpd. If this flow is multiplied by 0.9 to account for consumptive use, the study area average is 110 gpd.

In order to provide a check on the water use, the Falmouth Census average occupancies were multiplied by the state Title 5 estimate of 55 gpd of wastewater per capita results, The resulting flow estimates are 130 gpd of average estimated water use per residence based on 2000 Census occupancy and 123 gpd based on 2010 Census occupancy. 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. In other Falmouth MEP watersheds, these multipliers have helped to explain the average water use measured among residences in those watersheds, but in the Falmouth Inner Harbor watershed, the Census-based wastewater estimates closely match the measured water use. This finding suggests that residences in the Falmouth Inner Harbor watershed area are mostly occupied year-round. This analysis also 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 96% of the 536 developed parcels in the Falmouth Inner Harbor watershed. Developed 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 or town assessor valuations, and do not have a listed account in the water use databases. Of the 19 developed parcels without water use accounts, 15 (79%) are classified as commercial properties (land use codes in the 300s). These parcels are assumed to utilize private wells. Water use from commercial properties on average is less than single family residences, so these properties were conservatively assigned the Falmouth Inner Harbor study area average water use of 122 gpd in the watershed nitrogen loading modules. All developed residential properties without water use were also assigned this average water use.

Wastewater Treatment Facilities and Alternative Septic Systems

When developing watershed nitrogen loading information, MEP project staff typically seek additional information on enhanced wastewater treatment in the project study area. This information is reviewed and if judged reliable, is included in the watershed nitrogen loading model.

MEP staff received a list of alternative, denitrifying septic system in Falmouth and total nitrogen effluent monitoring data from the Barnstable County Department of Health and the Environment (personal communication, Brian Baumgaertel, BCDHE, 1/2011). From the BCDHE database, project staff identified four (4) denitrifying septic systems within the Falmouth Inner Harbor watershed. Two of these systems had more than three sampling runs and the wastewater nitrogen loading factor for these parcels was modified to reflect the average total nitrogen concentrations in their effluent. The other two systems did not have enough sampling to adjust the wastewater concentration for these sites and the standard MEP wastewater nitrogen factor was used for these sites in the watershed nitrogen loading model.

MEP staff also contacted MassDEP to review whether any Groundwater Discharge Permits (GWDPs) are on file for any sites in the Falmouth Inner Harbor watershed area. A GWDP is required under MassDEP regulations for wastewater treatment systems with design flows greater than 10,000 gallons per day. According the MassDEP databases, there is one GWDP in the watershed: the Atria Woodbriar site, which is located within the Morse Pond sub-watershed (sub-watershed #1). Using performance data in the BCDHE database, the annual wastewater nitrogen load from the site is calculated as 159 kg yr^{-1}. This load is included in the Falmouth Inner Harbor watershed nitrogen loading model.

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 Falmouth Inner Harbor system, MEP staff reviewed available regional information about residential lawn fertilizing practices and sought site-specific information for the following golf course: Woodbriar Golf Course. The Woodbriar Golf Course has recently been included in a redevelopment proposal and staff incorporated its load based on the timing of MEP water quality monitoring.

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, 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/lawn/yr.

The former Woodbriar Golf Course is located in the Jones Pond watershed and is part of a recently approved redevelopment project that will include 125 residential units (personal communication, Brian Currie, Falmouth Town Planner, 4/2011). Review of historical aerial photographs on Google Earth show that the golf course turf areas were maintained up until at least July 2007. Estuarine water quality sampling results for the MEP modeling are based on data collected in 2006-2010 and stream water quality sampling was for the period 2006-2007. For this reason, fertilizer applications from Woodbriar Golf Course are included in the existing conditions evaluation of Falmouth Inner Harbor.

As has been done in all MEP reviews, MEP staff reviewed the layout of the golf course from aerial photographs, classified the various turf types, and, using GIS, assigned these areas to the Jones Pond sub-watershed. When site-specific golf course fertilizer application rates are not available, MEP staff assign average application rates from courses that have provided this information. Current MEP nitrogen application rate averages (all in pounds per 1,000 square feet per year) based on reporting from 19 courses are: greens, 3.6; tees, 3.3; fairways, 3.3, and roughs, 2.5. These application rates, along with the standard MEP 20% leaching rate, are used in the Falmouth Inner Harbor watershed nitrogen loading model for the turf portions of the Woodbriar Golf Course that are in the watershed.

Nitrogen Loading Input Factors: Other

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

Road areas are based on MassHighway GIS information, which provides road width for various lengths of 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.

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 Falmouth Inner 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. The Town of Falmouth provided GIS coverages of building footprints for the roof area calculations. Individualized information for parcels with atypical nitrogen loading (denitrifying septic systems) 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 Falmouth Inner 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, sub-watershed modules were generated for each of the four (4) sub-watersheds in the Falmouth Inner Harbor study area. These sub-watershed modules summarize, among other things: water use, parcel area, parcel frequency by land use category, private wells, and road area. All relevant nitrogen loading data are assigned to each sub-watershed. Individual sub-watershed information is then integrated to create the Falmouth Inner Harbor Watershed Nitrogen Loading summary module with summaries for each of the individual four 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 Falmouth Inner Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Falmouth-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 parcels w/o water accounts and buildout single-family residential parcels:	122 gpd[2]
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (sq ft)[1]	5,000	Existing developed parcels w/water accounts:	Measured annual water use
Residential Watershed Nitrogen Rate (lbs/lawn)[1]	1.08	Commercial and Industrial Buildings buildout additions[3]	
Fertilizer leaching rate	20%	Commercial	
Atria Woodbriar GWDP annual nitrogen load (kg)[4]	159	Wastewater flow (gpd/1,000 ft2 of building):	180
		Building coverage:	15%
		Industrial	
Average Single Family Residence Building Size from watershed data (sq ft)	1,242	Wastewater flow (gpd/1,000 ft2 of building):	44
		Building coverage:	5%

Notes:
1) Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.
2) Based on average flow of all single-family residences in the watershed
3) based on existing water use and water use for similarly classified properties throughout the Town of Falmouth
4) Based on measured water use and available total nitrogen concentrations

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 Falmouth Inner Harbor study area, the major types of nitrogen loads are: wastewater (*e.g.*, from septic systems), wastewater treatment facilities, non-golf course fertilizers, golf course fertilizers, impervious surfaces, 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 contributing area of component sub-embayments, 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.

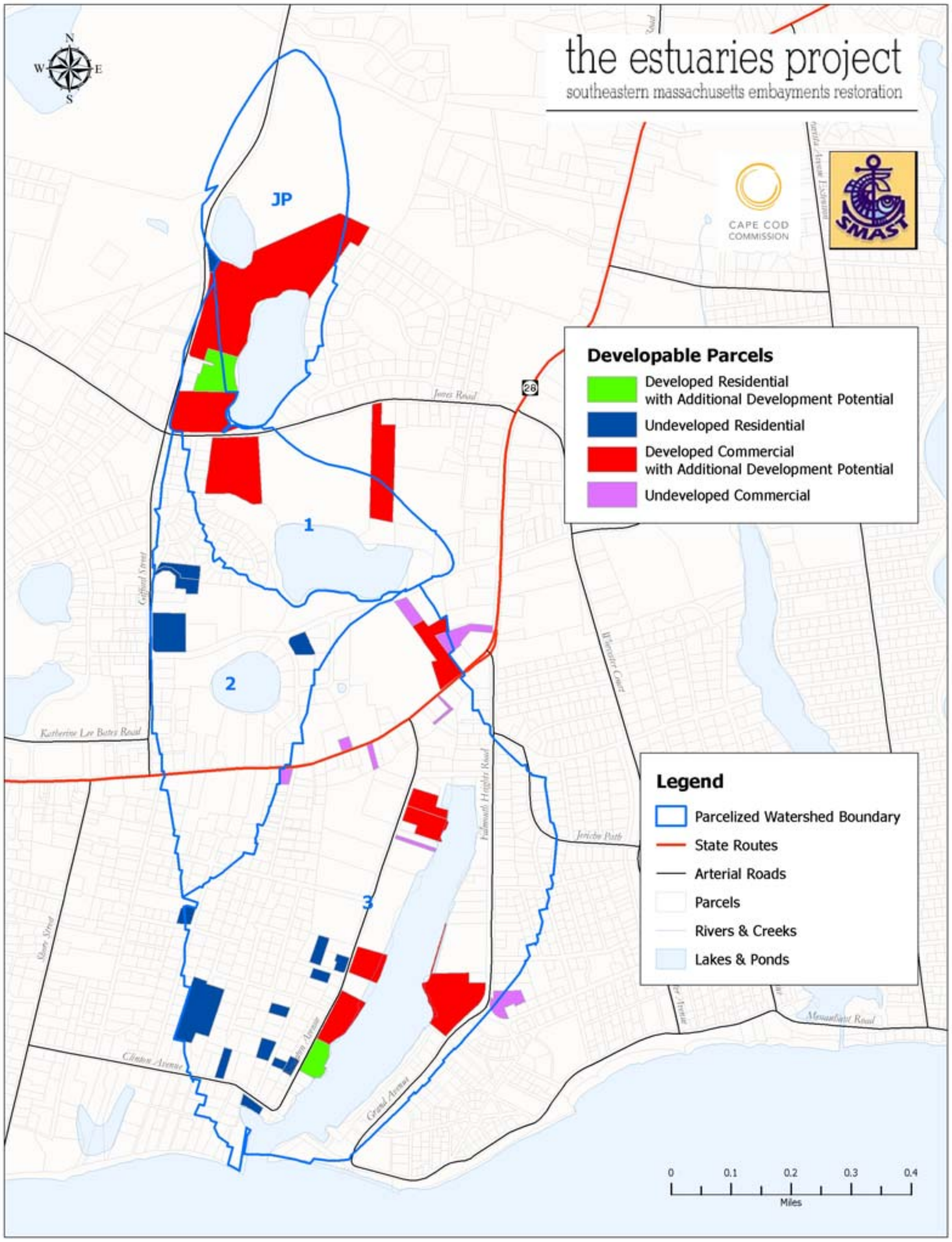

Figure IV-3. Parcels, Parcelized Watersheds, and Developable Parcels within the Falmouth Inner Harbor watersheds. Parcels colored green and red are developed parcels (residential and commercial, respectively) with additional development potential based on current zoning, while parcels colored blue and purple are undeveloped residential and commercial parcels respectively 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. Development potential is 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 (personal communication, Brian Currie, Town of Falmouth, 4/2011).

Table IV-3. Falmouth Inner Harbor Watershed Nitrogen Loads. Unattenuated nitrogen loads are a sum of all sources without including natural nitrogen attenuation in fresh surface waters. Attenuated nitrogen loads are based on measured and assigned attenuation factors for up-gradient streams and freshwater ponds. Stream attenuation factors are based on measured loads (see Section IV.2), while pond attenuation factors are assigned a standard MEP nitrogen attenuation rate of 50% based on regional water quality monitoring from the Cape Cod Pond and Lake Stewards program or a modified factor if sufficient site-specific monitoring data are available. All nitrogen loads are kg N yr^{-1}.

		Falmouth Inner Harbor N Loads by Input (kg/y):								% of Pond Outflow	Present N Loads			Buildout N Loads		
Watershed Name	Watershed ID#	On-site Wastewater	From WWTF	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
Falmouth Inner Harbor System		2,416	159	227	43	299	311	50	509		3,505		2,770	4,014		3,025
Falmouth Inner Hbr GT10	2	459	-	41	-	56	27	11	35		594		594	629	-	629
Falmouth Inner Hbr LT10	3	1,377	-	145	-	188	-	26	147		1,737		1,737	1,883	-	1,883
Morse Pond Total	MP	580	159	41	43	55	124	12	328	100%	1,014	70%	279	1,342	70%	352
Falmouth Inner Harbor Estuary Surface							160				160		160	160	-	160
Ponds																
Morse Pond Total	MP	580	159	41	43	55	124	12	328		1,014	70%	279	1,342	70%	352
Morse Pond	1	555	159	17	-	43	67	7	159		848		848	1,007		1,007
Jones Pond	JP	25	-	24	43	12	57	5	169	72%	166	50%	83	335	50%	167
Jones Pond	JP	34	-	33	60	16	79	7	233		229	50%	115	463	50%	231

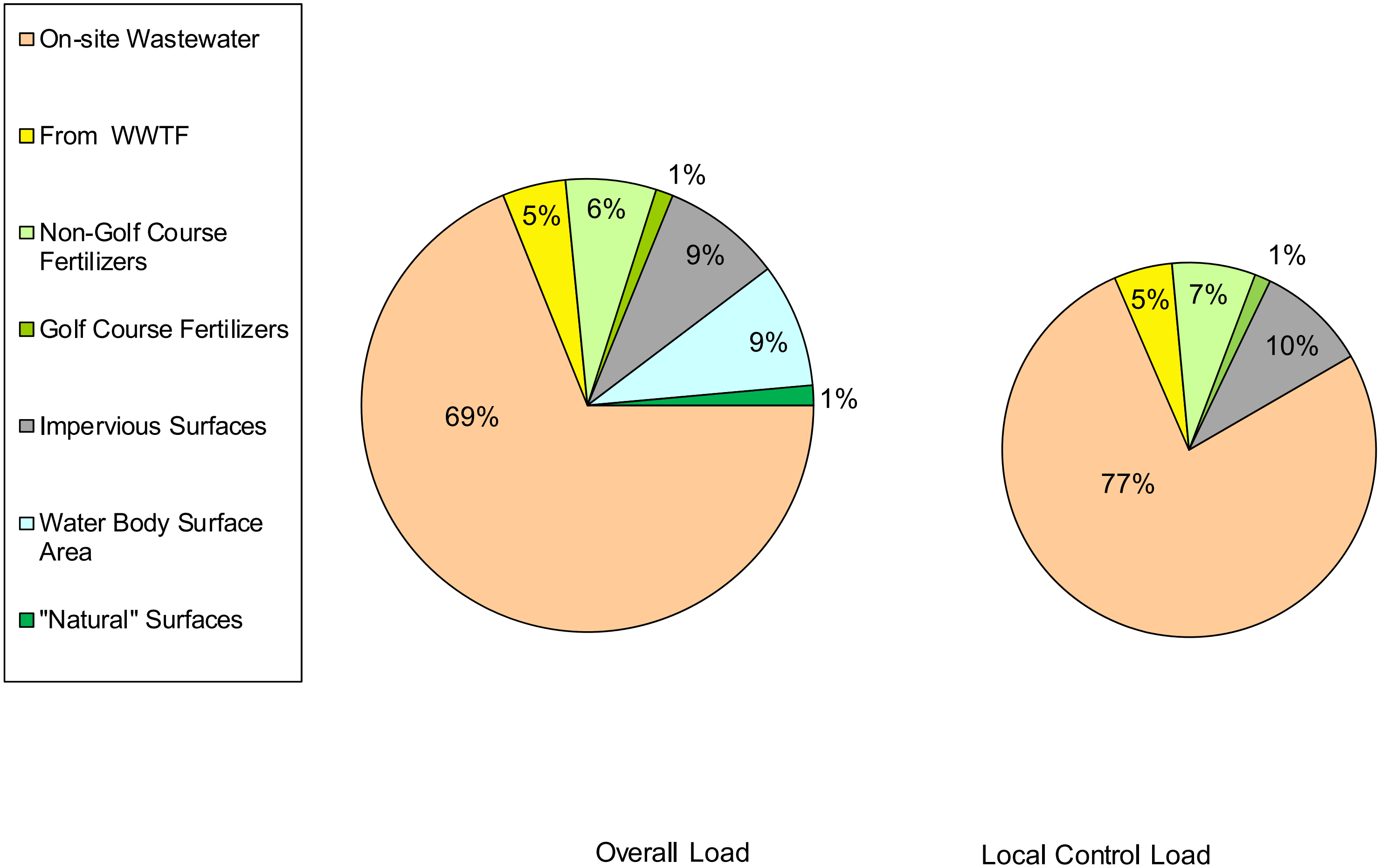

Figure IV-4. Land use-specific unattenuated nitrogen loads (by percent) to the whole Falmouth Inner Harbor watershed. “Overall Load” is the total nitrogen input within the watershed, while the “Local Control Load” represents those nitrogen sources that could potentially be under local regulatory control.

One of these attenuation adjustments occurs in the freshwater ponds. Since groundwater outflow from a pond can enter more than one down gradient sub-watershed, the length of shoreline on the down gradient side of the pond is used to apportion the pond-attenuated nitrogen load to respective down gradient watersheds. The apportionment is based on the percentage of discharging shoreline bordering each down gradient sub-watershed. In the Falmouth Inner Harbor study area, there are two ponds of sufficient size to have delineated sub-watersheds: Morse Pond and Jones Pond. Smaller ponds do not significantly affect the regional groundwater flow and the MEP does not delineate their contributing areas. Morse Pond is completely within the overall Falmouth Inner Harbor watershed, but Jones Pond is shared with the Little Pond MEP watershed, so its nitrogen load is split between the two watersheds.

Freshwater Pond Nitrogen Loads

Freshwater ponds on Cape Cod are generally watershed sites of natural nitrogen reduction (or attenuation) prior to the watershed nitrogen reaching an estuary. These ponds are generally kettle hole depressions of the land surface that intercept the surrounding groundwater table revealing what some call “windows on the aquifer.” Groundwater typically flows into the pond along the up-gradient shoreline, then lake water flows back into the groundwater system along the down gradient shoreline. Occasionally a Cape Cod pond will also have a stream outlet, which is often a herring run, that also acts as a discharge point. Since the nitrogen loads usually flow into a pond with the groundwater, the relatively more productive pond ecosystems incorporate some of the nitrogen, retain some nitrogen in the sediments, and change the nitrogen among its various oxidized and reduced forms. As result of these interactions, some of the nitrogen in the pond watershed is removed from the estuary watershed system, mostly through burial in pond sediments and denitrification that returns it to the atmosphere. Following these reductions, the remaining (attenuated) loads flow back into the groundwater system along the down gradient side of the pond and eventual discharge into the down gradient embayment or through a stream outlet directly to the estuary. The nitrogen load summary in Table IV-3 includes both the unattenuated (nitrogen load to each sub-watershed) and attenuated nitrogen loads.

Nitrogen attenuation in freshwater ponds has generally been found to be at least 50% in MEP analyses, so a conservative attenuation rate of 50% is generally assigned to all nitrogen from freshwater pond watersheds in the watershed model unless more detailed pond monitoring or studies are available. Detailed studies of other southeastern Massachusetts freshwater systems including Ashumet Pond (AFCEE, 2000) and Agawam/Wankinco River Nitrogen Discharges (CDM, 2001) have supported a 50% attenuation factor as a reasonable, somewhat conservative rate. However, in some cases, if sufficient monitoring information is available, a pond-specific attenuation rate is incorporated into the watershed nitrogen loading modeling (*e.g.*, 87%, Mystic Lake; 40%, Middle Pond; and 52%, Hamblin Pond in the Three Bays MEP Report, Howes, *et al*., 2006). In order to review whether a pond-specific nitrogen attenuation rate other than 50% should be used, the MEP Technical Team reviews the available data on each pond, including available nitrogen concentrations, impacts of sediment regeneration, temperature profiles, and bathymetric information.

Bathymetric information is generally a prerequisite for determining enhanced attenuation, since it provides the volume of the pond and, with appropriate pond total nitrogen concentrations, a measure of the nitrogen mass in the water column. Combined with the watershed recharge, this information can provide a residence or turnover time that is necessary to gauge pond-specific nitrogen attenuation.

In addition to bathymetry, temperature profiles are useful to help understand whether temperature stratification is occurring in a pond. If the pond has an epilimnion (*i.e.*, a well-mixed, relatively isothermic, warm, upper portion of the water column) and a hypolimnion (*i.e.*, a deeper, colder layer), the stability and volume of these two layers must be accounted for in the nitrogen attenuation calculations. In these stratified lakes, the upper epilimnion is usually the primary discharge for watershed nitrogen loads; the deeper hypolimnion generally does not interact with the upper layer. However, deep lakes with hypolimnions often also have significant sediment regeneration of nitrogen and in any lakes with impaired water quality this regenerated nitrogen can impact measured nitrogen concentrations in the upper epilimnion and this impact should also be considered when estimating nitrogen attenuation. Sediment nitrogen regeneration can also occur in shallow ponds as well.

Many ponds on Cape Cod have been sampled through the regional Cape Cod Pond and Lake Stewards (PALS) Snapshots and the initiative of local volunteer pond sampling programs. The PALS Snapshots are regional volunteer pond one-time sampling supported for the last nine years by SMAST and the Cape Cod Commission, with free laboratory services provided by the Coastal Systems Program Laboratory at SMAST. Sampling protocols developed through the PALS program (Eichner *et al*., 2003) have been used for more extensive pond sampling programs in many communities on Cape Cod. Sampling under these protocols has included field collection of temperature and dissolved oxygen profiles and sampling has generally occurred at standardized depths that provide some evaluation of potential sediment nutrient regeneration. PALS water samples are analyzed at the SMAST laboratory for total nitrogen, total phosphorus, chlorophyll-*a*, alkalinity, and pH. In some cases town programs have generated sufficient sampling data that modified MEP nitrogen attenuation rates can be reliably assigned to freshwater ponds.

Within the Falmouth Inner Harbor watershed, there are two freshwater ponds with delineated watersheds: Morse Pond and Jones Pond. Neither pond has been sampled during the nine years of the PALS Snapshots and review of other available sources has not provided any water quality data. Neither pond has available pond-wide bathymetric data (Eichner *et al*., 2003) or sufficient water quality measurements to support a pond-specific attenuation analysis by the MEP.

Although neither freshwater pond has sufficient in-pond sampling to assign a pond-specific nitrogen attenuation rate, MEP staff did install a stream gauge at the stream outlet of Morse Pond. Based upon the water quality and flow information collected from this gauge (see Section IV.2) and the unattenuated nitrogen load contributed from the watershed above the gauge site, the MEP Technical Team determined that Morse Pond was attenuating 70% of the nitrogen prior to reaching the gauge site. This attenuation rate is a balance between the measured flow and load leaving the pond through the stream gauge. Jones Pond is assigned the standard 50% MEP pond nitrogen attenuation rate. Jones Pond was also assigned the standard MEP pond 50% nitrogen attenuation rate in the Little Pond MEP assessment (Howes, *et al.*, 2006).

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) residential, commercial and industrial 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 the initial 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, usually 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 may include 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.

Other provisions of the MEP buildout assessment include differentiated treatment of undevelopable lots, commercial and industrial properties, and lots less than the minimum areas specified by zoning. Properties classified by the Town of Falmouth assessors as "undevelopable" (*e.g.*, MassDOR codes 132, 392, and 442) are not assigned any development at buildout (unless revised by the town review). 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. Most town zoning bylaws have a lower minimum lot size for pre-existing lots (usually 5,000 square feet) that will minimize instances of regulatory takings. Existing developed residential properties that are larger than zoning's minimum lot sizes are also assigned additional development potential only if enough area is available to accommodate at least one additional lot as specified by the zoning minimum.

Following the completion of the initial buildout assessment for the Falmouth Inner Harbor watersheds, MEP staff reviewed the results with Brian Currie, Falmouth Town Planner in April 2011. Suggested changes from town staff review were incorporated into the final buildout for Falmouth Inner Harbor.

All the parcels with additional buildout potential within the Falmouth Inner 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 standard on-site septic systems except for the Woodbriar Golf Course redevelopment project. None of the buildout additions are assumed to be connected to the municipal sewer system.

Based on conversations with Brian Currie, Falmouth Town Planner (personal communication, 4/2011), the Woodbriar Golf Course redevelopment project is assumed to have 125 residential units. Each of these units is assumed to use the average water use in the Falmouth Inner Harbor watershed (127 gpd), which results in a cumulative estimated wastewater flow greater than the state GWDP threshold. It is further assumed that since the redevelopment will require a GWDP, the effluent from the future wastewater treatment facility will need to achieve a 10 mg/l total nitrogen concentration. The buildout load from this site includes the addition of this wastewater load and the removal of the golf course fertilizer load.

Cumulative unattenuated buildout loads from all sub-watersheds are indicated in a separate column in Table IV-3. Buildout additions within the Falmouth Inner Harbor watersheds will increase the unattenuated system-wide nitrogen loading rate by 15%.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

IV.2.1 Background and Purpose

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out, sewering analysis, enhanced flushing, pond/wetland restoration for natural attenuation, etc.) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the sub-watersheds of the Falmouth Inner Harbor Embayment System being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1).

If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such as the developed regions of the Falmouth Inner Harbor watersheds). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. However, in most watersheds in southeastern Massachusetts, nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the watershed for the Falmouth Inner Harbor embayment system, a portion of the freshwater flow and transported nitrogen passes through a pond (Morse Pond) with a discrete discharge point (e.g. a culvert discharging into the head of Falmouth Inner Harbor) prior to entering the broader estuary, producing the opportunity for reductions in nutrient loading, primarily through nitrogen attenuation.

Failure to determine the attenuation of watershed derived nitrogen overestimates the nitrogen load to receiving estuarine waters. If nitrogen attenuation is significant in one portion of a watershed and insignificant in another the result is that nitrogen management would likely be more effective in achieving water quality improvements if focused on the watershed region having unattenuated nitrogen transport (other factors being equal). In addition to attenuation by freshwater ponds (see Section IV.1.3, above), attenuation in surface water flows is also important. An example of the significance of surface water nitrogen attenuation relating to embayment nitrogen management was seen in the Agawam River, where >50% of nitrogen originating within the upper watershed was attenuated prior to discharge to the Wareham River Estuary (CDM 2000). Similarly, MEP analysis of the Quashnet River indicates that in the upland watershed, which has natural attenuation predominantly associated with riverine processes, the integrated attenuation was 39% (Howes et al. 2004). In addition, a preliminary study of Great, Green and Bournes Ponds in Falmouth, measurements indicated a 30% attenuation of nitrogen during stream transport (Howes and Ramsey 2001). An example where natural attenuation played a significant role in nitrogen management can be seen relative to West Falmouth Harbor (Falmouth, MA), where ~40% of the nitrogen discharge to the Harbor originating from the groundwater effluent plume emanating from the WWTF was attenuated by a small salt marsh prior to reaching Harbor waters. Clearly, proper development and evaluation of nitrogen management options requires determination of the nitrogen loads reaching an embayment, not just loaded to the watershed.

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP Approach in the Falmouth Inner Harbor embayment system. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the perimeter of the embayment system in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). These additional site-specific studies were conducted in the 1 major surface water flow system in the Falmouth Inner Harbor watershed, Morse Pond discharging to the head of Falmouth Inner Harbor (Figure IV-5). Unlike, many streams and creeks in the MEP study region, the outflow from Morse Pond consists of a natural stream channel for a short length and then the flow enters a concrete pipe that flows under a developed area of Falmouth prior to discharging into Falmouth Inner Harbor. The stream flow in the concrete pipe is tidally influenced.

Quantification of watershed based nitrogen attenuation is contingent upon being able to compare nitrogen load to the embayment system directly measured in freshwater stream flow (or in tidal marshes, net tidal outflow) to nitrogen load as derived from the detailed land use analysis (Section IV.1). Measurement of the flow and nutrient load associated with the freshwater stream discharging to the estuary provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up gradient from the various gaging sites. Flow and nitrogen load was determined at one gauge location immediately down gradient of Morse Pond for 16 months of record (Figure IV-6), though for portions of the deployment period there was no flow in the stream due to dry conditions during the summer. During the study period, a velocity profile was completed at the gauge positioned in the small natural channel formed down gradient of the culvert discharging from Morse Pond. Velocity profiles were completed at the gauge every month to two months. The summation of the products of stream subsection areas of the channel cross-section and the respective measured velocities represent the computation of instantaneous flow (Q).

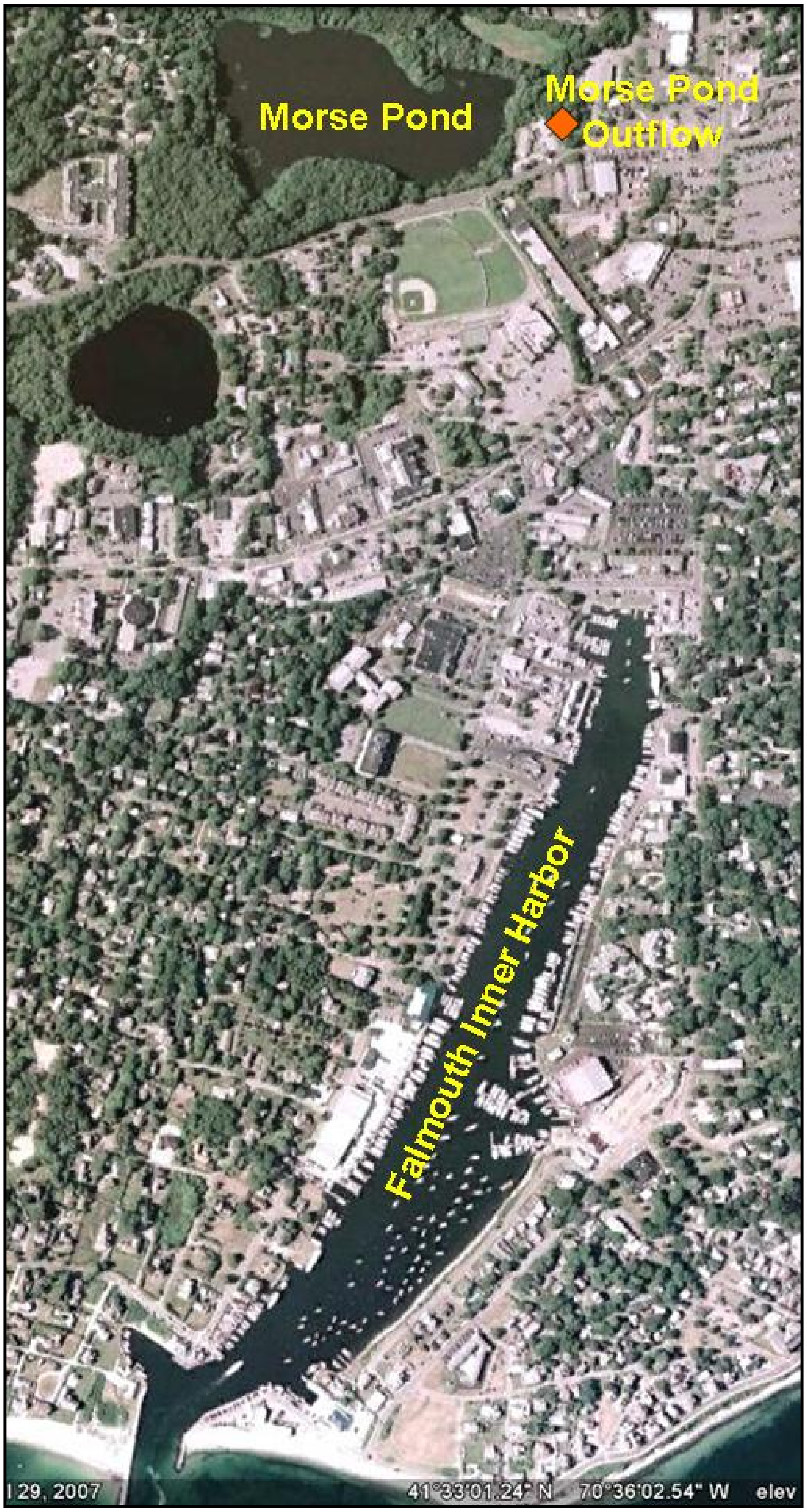

Figure IV-5. Location of the Stream gauge (red symbol) within the watershed to the Falmouth Inner Harbor Embayment. The site was monitored to determine freshwater flow and nitrogen load to the estuary. Freshwater flow from Morse Pond exits through a culvert to a small shallow stream channel to a tidally influenced concrete pipe that discharges to the head of the Falmouth Inner Harbor estuary.

Determination of flow at the gauge positioned down gradient of the culvert discharging from Morse Pond to Falmouth Inner Harbor was calculated and based on the measured values obtained for the cross sectional area of the stream as well as stream specific velocity. Freshwater discharge was represented by the summation of individual discharge calculations for each channel subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire channel cross section were not averaged and then applied to the total stream cross sectional area.

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

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

where by:

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

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

Periodic measurement of flows over the entire “stream” gauge deployment period allowed for the development of a stage-discharge relationship (rating curve) that could be used to obtain flow volumes from the detailed record of stage measured by the continuously recording stream gauge. Water level data obtained every 10-minutes was averaged to obtain hourly stages for the gauge location. These hourly stages values where then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. A complete annual record of flow in the stream (365 days) was generated for the surface water discharge flowing into the head of Falmouth Inner Harbor embayment and emanating from Morse Pond.

The annual flow record for the surface water flow at the gauge was merged with the nutrient data set generated through the weekly water quality sampling performed at the gauge location to determine nitrogen loading rates to the head of harbor. Nitrogen discharge from the small stream capturing the freshwater discharge from Morse Pond was calculated using the paired daily discharge and daily nitrogen concentration data to determine the mass flux of nitrogen through the gaging site. For the stream gauge location, weekly water samples were collected in order to determine nutrient concentrations from which nutrient load was calculated when merged with the flow record. In order to pair daily flows with daily nutrient concentrations, interpolation between weekly nutrient data points was necessary. These data are expressed as nitrogen mass per unit time (kg/d) and can be summed in order to obtain weekly, monthly, or annual nutrient load to the embayment system as appropriate. Comparing these measured nitrogen loads based on flow in the stream and water quality sampling to predicted loads based on the land use analysis allowed for the determination of the degree to which natural biological processes within the watershed to the gaging point currently reduces (percent attenuation) nitrogen loading to the overall embayment system.

IV.2.3 Surface Water Discharge and Attenuation of Watershed Nitrogen: Morse Pond Discharge into Falmouth Inner Harbor

Morse Pond is a small freshwater pond and unlike many of the freshwater ponds on Cape Cod, this small pond has a small direct freshwater discharge to the Falmouth Inner Harbor embayment rather than draining solely to the aquifer along its down-gradient shore. This outflow through the culvert discharging to an un-named stream, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation occurring in the pond. In addition, nitrogen attenuation also occurs within a small portion of natural streambed and riparian zone associated with the stream prior to its entry into a concrete pipe passing under a highly urbanized area on the way to the head of Falmouth Inner Harbor. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the stream above the gauge site and the measured annual discharge of nitrogen to the stream flowing into the head of Falmouth Inner Harbor, Figure IV-5.

At the gauge site (situated immediately down-gradient of the Morse Pond Culvert), a continuously recording vented calibrated water level gauge was installed to yield the level of water in the freshwater stream discharging from Morse Pond and which carries the flows and associated nitrogen load to the head of the Falmouth Inner Harbor embayment. As the small stream is tidally influenced in the concrete pipe between Morse Pond and the discharge point in the estuary, the gauge was located as far down gradient along the natural stream reach such that freshwater flow could be measured at low tide. Based on the stage record, the location of this specific gauge was not tidally influenced. This was further confirmed by salinity measurements conducted on the weekly water quality samples collected from the gauge site. Average salinity for all the water samples collected over the entire gauge deployment period was determined to be 0.1 ppt. As such, the overall flow record ***did not*** have to be adjusted for salinity influence at the gauge location in order to quantify freshwater flow in the stream. As there was no salinity influence, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked approximately monthly each time the site was visited and a flow measurement obtained. The gauge on the stream was installed on May 26, 2006 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued until November 9, 2007 for a total deployment of 18 months, however, the last few months of the deployment the streambed was dry due to low flow conditions.

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the un-named stream site based upon these flow measurements and measured water levels at the gauge site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the head of the Falmouth Inner Harbor embayment. This measured attenuated mass discharge is reflective of the biological processes occurring primarily in Morse Pond as there was very little natural channel reach above or below the gauge site (Figure IV-6 and Table IV-4). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at the gauge site.

The annual freshwater flow record for the stream receiving water from the Morse Pond culvert as measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from the stream was 11% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for one hydrologic year beginning September 1, 2006 and ending August 31, 2007 (low flow to low flow) was 786 m^3/day compared to the long term average flows determined by the USGS modeling effort (871 m3/day) (Table IV-5).

Table IV-4. Comparison of water flow and nitrogen discharges from the freshwater discharge from Morse Pond to the tidally influenced Falmouth Inner Harbor embayment. The "Stream" data are from the MEP stream gauging effort. Watershed data are based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	**Morse Pond Discharge**[(a)] Falmouth Inner Harbor	**Data Source**
Total Days of Record	365[(b)]	(1)
Flow Characteristics		
Stream Average Discharge (m3/day) **	786	(1)
Contributing Area Average Discharge (m3/day)	871	(2)
Discharge Stream 2006-07 vs. Long-term Discharge	-11%	
Nitrogen Characteristics		
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.047	(1)
Stream Average Total N Concentration (mg N/L)	0.777	(1)
Nitrate + Nitrite as Percent of Total N (%)	6%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	0.61	(1)
TN Average Contributing UN-attenuated Load (kg/day)	2.55	(3)
Attenuation of Nitrogen in Pond/Stream (%)	76%	(4)

(a) Flow and N load to stream discharging from Morse Pond to Falmouth Inner Harbor includes apportionments of Pond contributing areas for ponds upgradient of Morse Pond.
(b) June 5, 2006 to June 4, 2007.
** Flow is an average of annual flow for 2006-2007

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

The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the stream was considered to be negligible given the relatively small flow and associated load. The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in stream discharging from Morse Pond would indicate that the stream is capturing the up-gradient recharge (and loads) accurately.

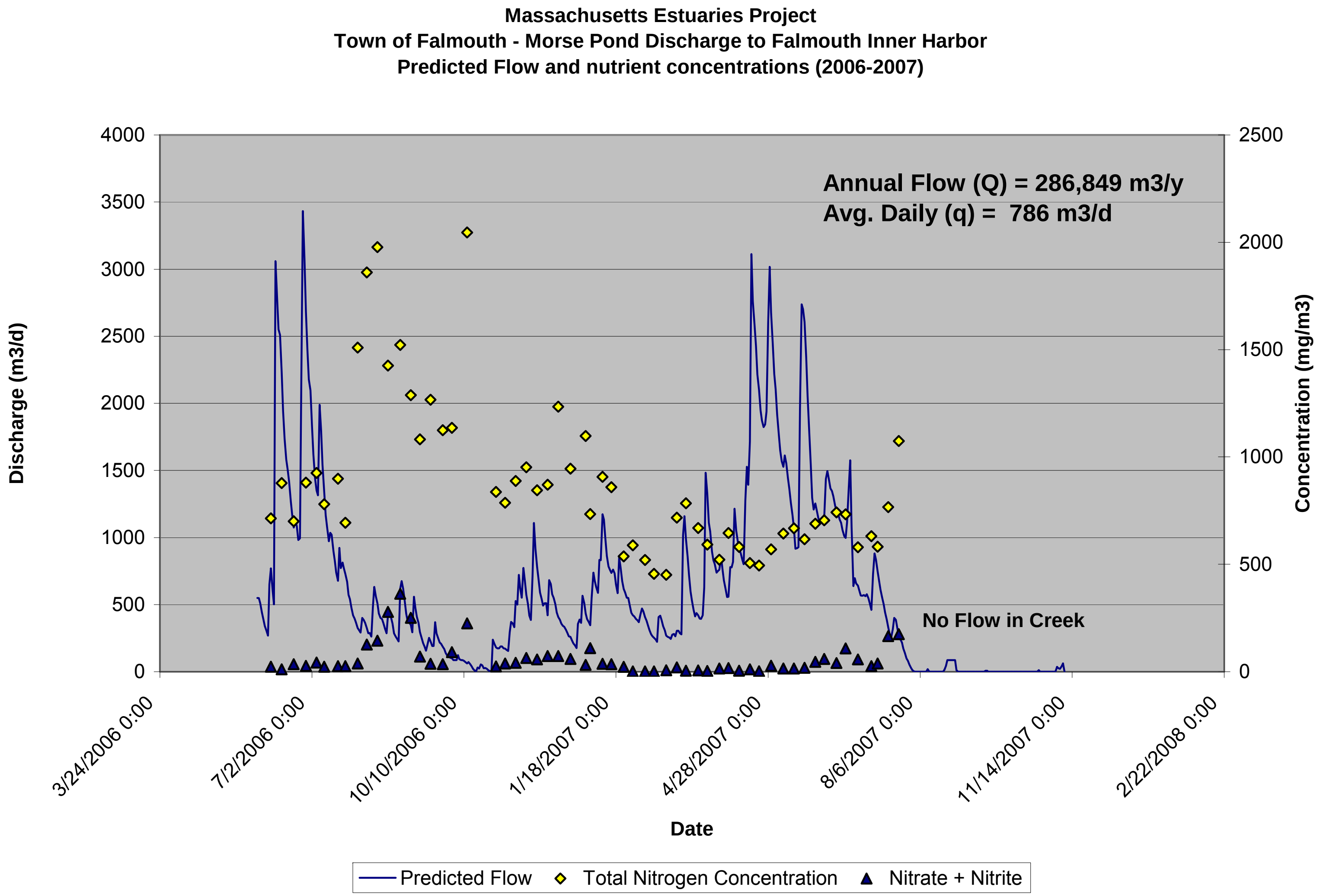

Figure IV-6. Morse Pond discharging directly into the head of the Falmouth Inner (solid blue line), nitrate+nitrite (blue symbol) and total nitrogen (yellow symbol) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Falmouth Inner Harbor (Table IV-4).

Table IV-5. Summary of annual volumetric discharge and nitrogen load from Morse Pond discharging directly to the head of Falmouth Inner Harbor. Flows and loads based upon the data presented in Figures IV-6 and Table IV-4.

Embayment System	Period of Record	Discharge (m^3/year)	Attenuated Load (Kg/year)	
			Nox	TN
Falmouth Inner Harbor Morse Pond Discharge (MEP)	June 5, 2006 to June 4, 2007	286,849	11	223
Falmouth Inner Harbor Morse Pond Discharge (CCC)	Based on Watershed Area and Recharge	317,915	-	-

Total nitrogen concentrations within the stream outflow were moderate, 0.777 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 0.61 kg/day and a measured total annual TN load of 223 kg/yr. In the stream (freshwater), nitrate was significantly less than half of the total form of nitrogen (6%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to Morse Pond was largely converted to organic forms by natural biological processes occurring within the pond system. The dissolved and particulate organic nitrogen constitute ~90% of the total nitrogen pool within the stream water entering Falmouth Inner Harbor. In addition, the low nitrate level (0.047 mg N L^{-1}) suggests the possibility for additional uptake by freshwater systems up-gradient from the gauge location is unlikely, unless it involves processes that increase the retention of particulate nitrogen. This suggests that it may not be possible to significantly enhance natural attenuation in Morse Pond.

From the measured nitrogen load discharged by the stream to Falmouth Inner Harbor and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower total nitrogen load (223 kg yr^{-1}) discharged from the freshwater stream compared to that added by the various land-uses to the associated watershed (931 kg yr^{-1}), the integrated attenuation in passage through Morse Pond prior to discharge to the estuary is 76% (i.e. 76% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the hydrologic and biogeochemical characteristics of the up-gradient pond capable of attenuating nitrogen. The directly measured nitrogen loads from the stream was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the benthic nutrient flux surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters throughout the Falmouth Inner Harbor Embayment. 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 Falmouth Inner 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 Vineyard Sound). 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 the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading to the Falmouth Inner 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 Falmouth Inner Harbor Embayment System, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. A total of 12 cores were collected from 10 sites (Figure IV-7) in July-August 2007, focusing on obtaining an areal distribution that would be representative of nutrient fluxes throughout the system but also considering tributary "basins" such as the small boat basin near the mouth of the system. Duplicate cores were taken at two sites. 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 located at the municipal boat ramp. 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-7.

Falmouth Inner Harbor System Benthic Nutrient Regeneration Cores

- FLH-1 1 core (Lower Basin)
- FLH-2 1 core (Lower Basin)
- FLH-3 1 core (Lower Basin)
- FLH-4 1 core (Lower Basin)
- FLH-5 1 core (Lower Basin
- FLH-6 1 core (Lower Basin)
- FLH-7/8 2 cores (Upper Basin)
- FLH-8 1 core (Upper Basin)
- FLH-9 1 core (Upper River)
- FLH-10/11 2 cores (Upper River)
- FLH-11 1 core (Upper River)
- FLH-12 1 core (Upper River)

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.

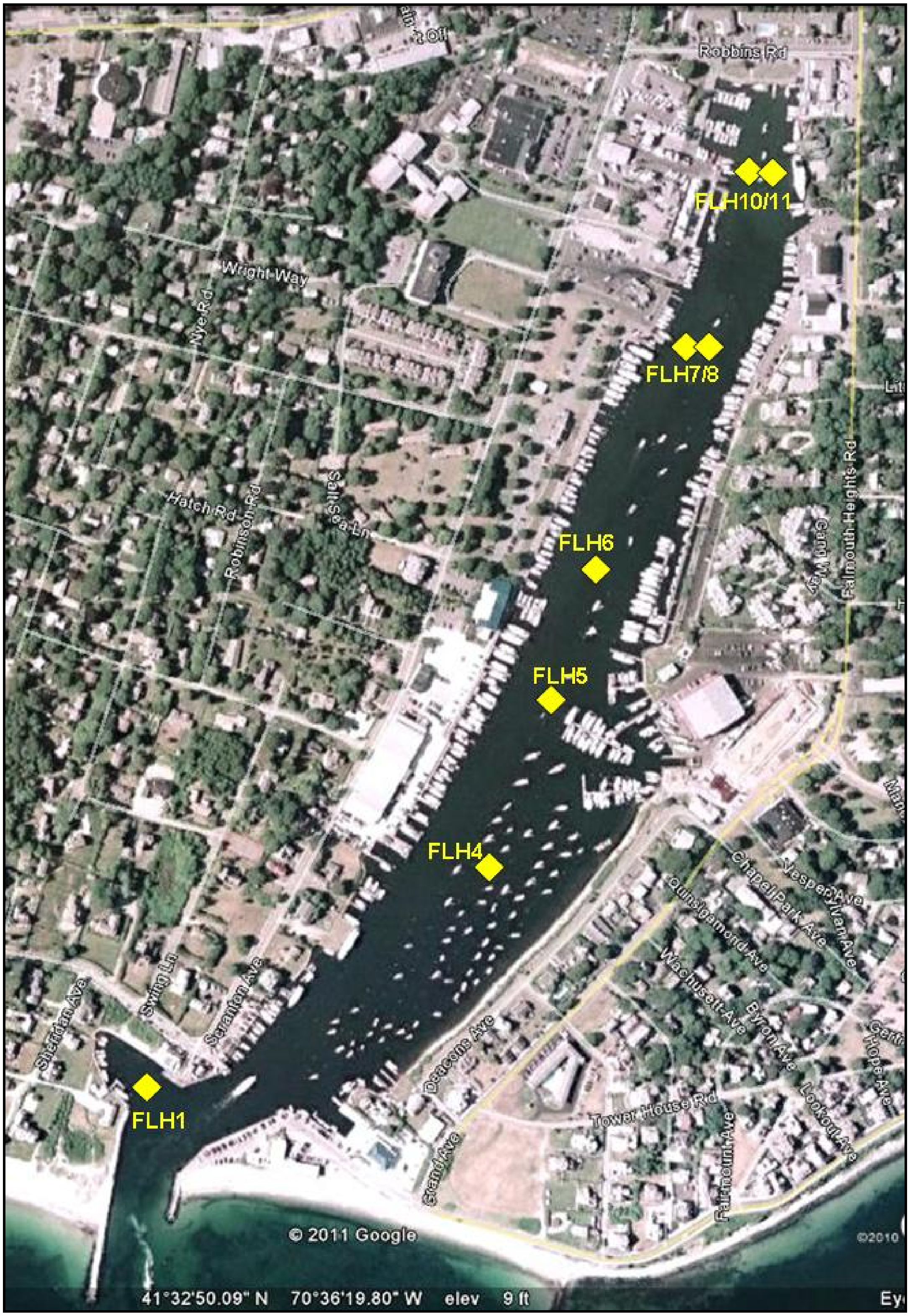

Figure IV-7. Falmouth Inner Harbor System locations (yellow symbols) of sediment sample collection for determination of nitrogen regeneration rates. Numbers relate to station i.d.'s referenced in Table IV-6.

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 (Brewer Fiddlers Cove Marina), 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 the 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-8).

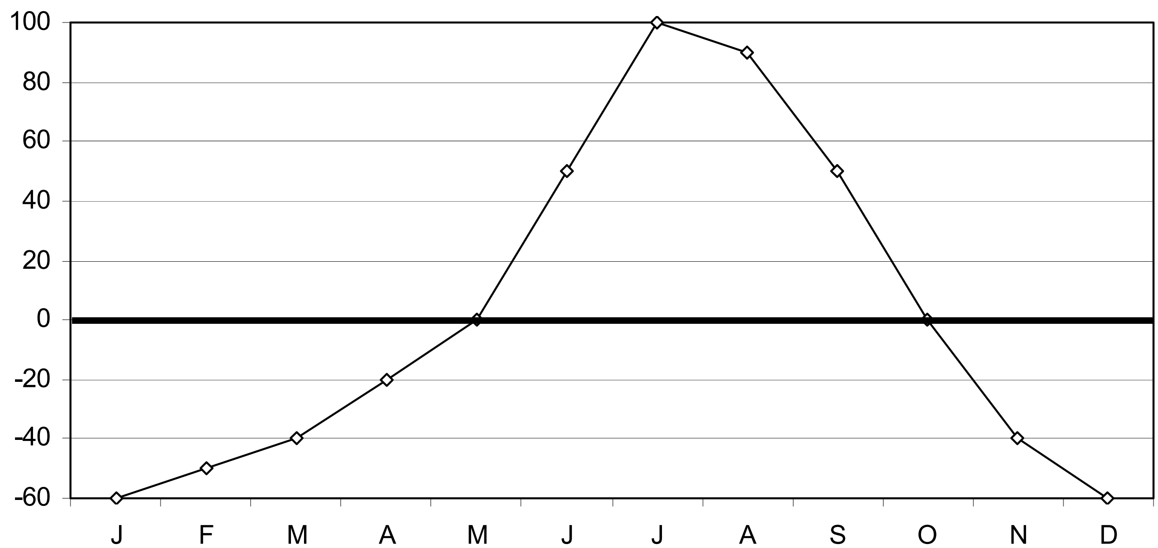

Figure IV-8. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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 upper and lower portions of the Falmouth Inner Harbor Embayment 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 Falmouth Inner Harbor system with the exception of the area in the immediate vicinity of the inlet to the Harbor. 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). Depositional areas were also determined from an analysis of the sediment type. Based upon the low velocities, a water column particle residence time of ~8 days was generally used (based upon phytoplankton and particulate carbon studies of poorly flushed basins), but in high velocity areas (e.g. inlet and channel) the rate was adjusted by half. 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 Falmouth Inner Harbor embayment system were comparable to other embayments of similar depth and configuration in southeastern Massachusetts. Rates of net nitrogen release generally showed slightly lower rates in the upper versus lower basin, 18.3 and 11.5 mg N m^{-1} d^{-1}, respectively, consistent with the spatial distribution of organic particles and phytoplankton biomass within the embayment waters. The spatial pattern of sediment-water column exchange is also consistent with basin morphology, sediment type and water depth. Similarly the net nitrogen release rates throughout Falmouth Inner Harbor were comparable to other embayments of similar depth and configuration in southeastern Massachusetts.

Fiddlers Cove and Rands Harbor are also artificially created open water embayments along the Town of Falmouth's Buzzards Bay coast. These embayments showed both similar overall rates and a similar gradient in nitrogen release from their upper to lower reaches, Fiddlers Cove 35.6 and 14.7 mg N m^{-1} d^{-1} and Rands Harbor (North Branch 27.0 and 21.3 mg N

m^{-1} d^{-1}, respectively. Another comparable embayment basin, Lagoon Pond (Martha's Vineyard) like much of Falmouth Inner Harbor, Rands Harbor and Fiddlers Cove has sediments consisting mainly of organic enriched muds with some sands. Lagoon Pond also shows similar rates of summertime nitrogen release within its semi-enclosed inner depositional basins, 8.4 and 31.8 mg N m^{-2} d^{-1}, as do the enclosed basins of Polpis Harbor (East Polpis, 14.6 mg N m^{-1} d^{-1}; West Polpis 65.9 mg N m^{-1} d^{-1}). Overall, the summer sediment nitrogen release from the sediments within the component basins of the Falmouth Inner Harbor System are comparable to other similarly configured enclosed basins, appear to be in balance with the overlying waters and 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 (upper and lower) of the Falmouth Inner Harbor System (Chapter VI) are presented in Table IV-6.

Table IV-6. Rates of net nitrogen return from sediments to the overlying waters of the Falmouth Inner 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	
Falmouth Inner Harbor Embayment System				
Upper Basin	18.3	14.3	6	7-12
Lower Basin	11.5	5.4	5	1,3,4,5,6**

* Station numbers refer to Figures IV-6.
** Station 2 was sampled but the sediment had been physically disturbed (localized disturbance).

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes the field data collection efforts and the development of hydrodynamic models for the Falmouth Inner 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 Falmouth Inner 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. Vineyard Sound). Several embayment-specific parameters influence tidal flushing and the associated residence time of water within an estuary. For the Falmouth Inner 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 surface water) 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 Falmouth Inner Harbor system (Figure V-1) is a tidally dominated embayment, with a southern opening to Vineyard Sound on the south side of Falmouth, MA. The harbor is roughly 37 acres in size and lined with docks, marinas and private piers for the mooring and protection of small boats.

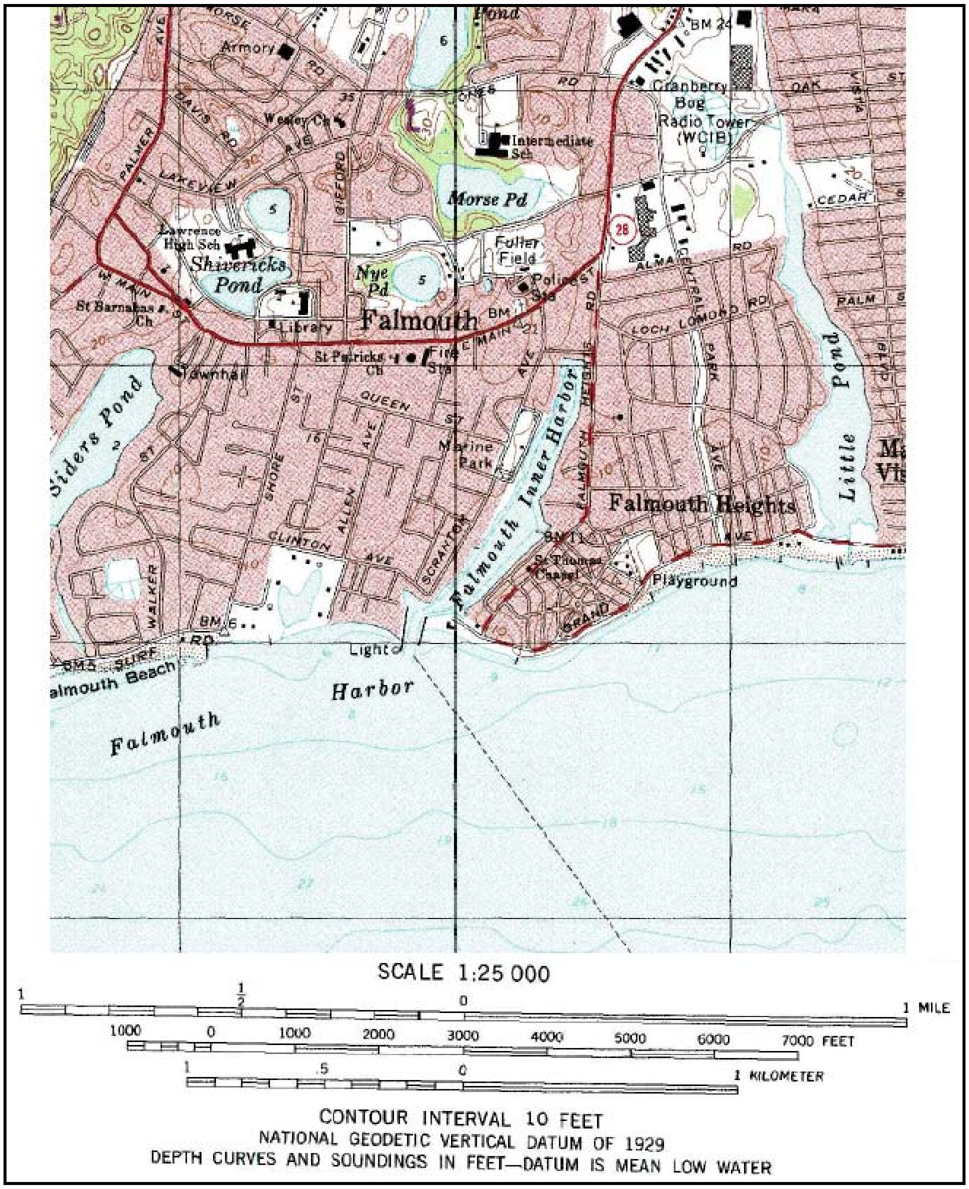

Figure V-1. Map of the Falmouth Inner Harbor estuary system (from United States Geological Survey topographic maps).

Since the water elevation difference between Vineyard Sound and the estuarine system is the primary driving force for tidal exchange of Falmouth Inner Harbor, the local tide range limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) along the length of Falmouth Inner 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 Vineyard Sound.

Circulation in the Falmouth Inner 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 gauge station installed in Vineyard Sound and at one location within the system (Figure V-2). All temperature-depth recorders (TDRs or tide gauges) were installed for a 39-day period to measure tidal variations through one complete tidal month, which is made up of two neap to spring 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) gauges were deployed for a 39-day period between April 22, and May 30, 2007. Each yellow dot represents the approximate locations of the tide gauges: (S-1) represents the Falmouth Inner Harbor gauge and (S-2) the Vineyard Sound gauge (Offshore).

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 a 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 Vineyard Sound. 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 a single interior location to measure variations of water surface elevation along the length of the system (gauge locations are shown in Figure V-2). These measurements were used to calibrate and verify the model results, and to assure that the dynamic of the physical system were properly simulated.

V.2.1 Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Falmouth Inner Harbor was assembled from a recent hydrographic survey performed specifically for this study. NOAA Coastal Services LIDAR survey data, where available, were used for areas of Falmouth Inner Harbor that were not covered by the more recent surveys.

The hydrographic survey was conducted in early May 2007. Survey transects were densest in the vicinity of the inlet, were the greatest variability in bottom bathymetry was expected. Bathymetry in the inlet is important from the standpoint that it has the most influence on tidal circulation in and out of the estuary. The survey was conducted from a shoal 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 National Geodetic Vertical Datum of 1929 (NGVD29) 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 survey showed an average depth of roughly 8.7 feet with a maximum depth of 16 feet near the head of the harbor.

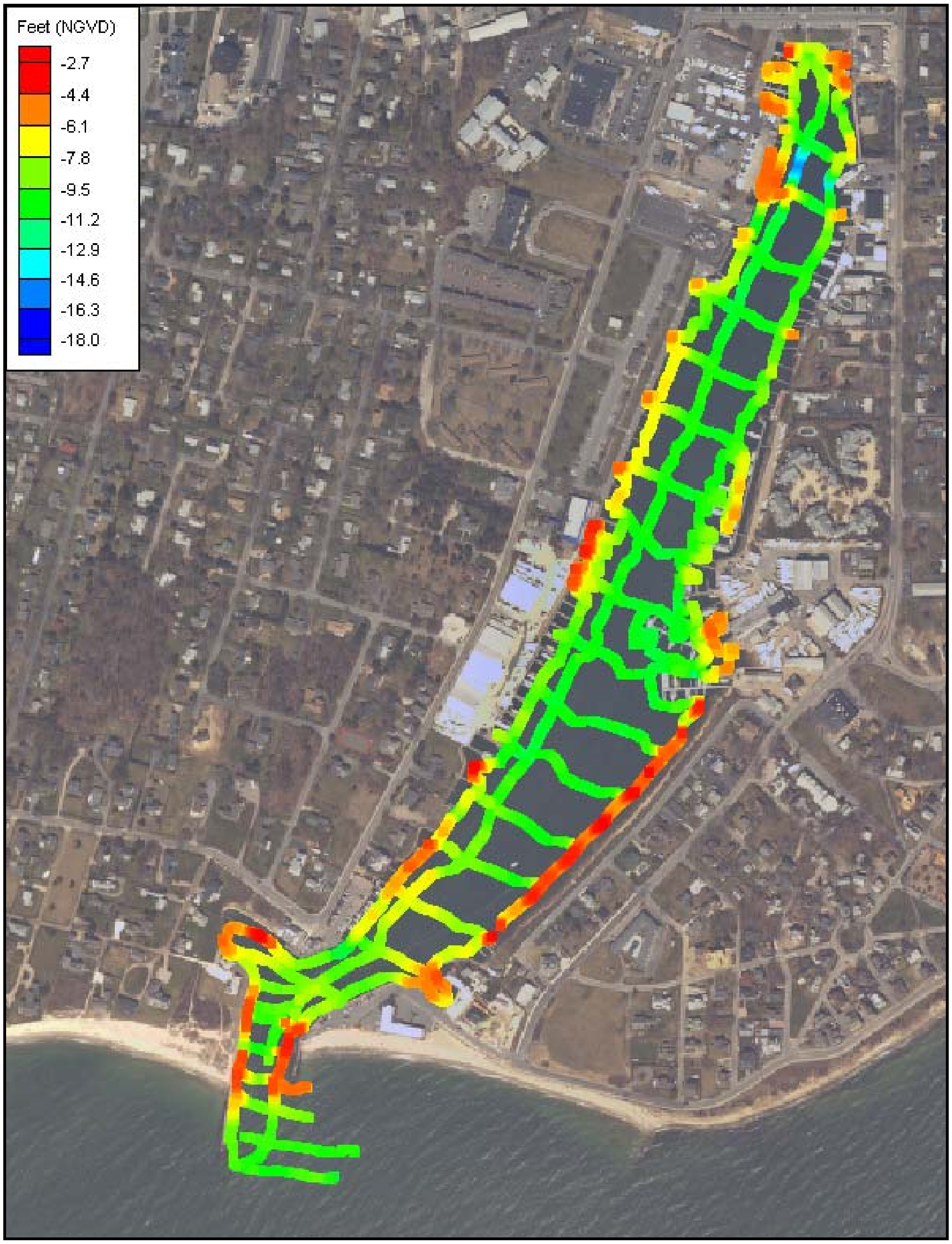

Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

V.2.2 Tide Data Collection and Analysis

Variations in water surface elevation were measured at a station in Falmouth Inner Harbor and at a station in Vineyard Sound. The offshore station (S-2) is located in Vineyard Sound. The Falmouth Inner Harbor station (S-1) is located at Falmouth Boat Yard on the northwest of the estuary. TDRs were deployed at each gauge 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 Falmouth Inner Harbor were corrected for atmospheric pressure variations and then rectified to the NGVD29 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 38-day period of the TDR deployment.

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

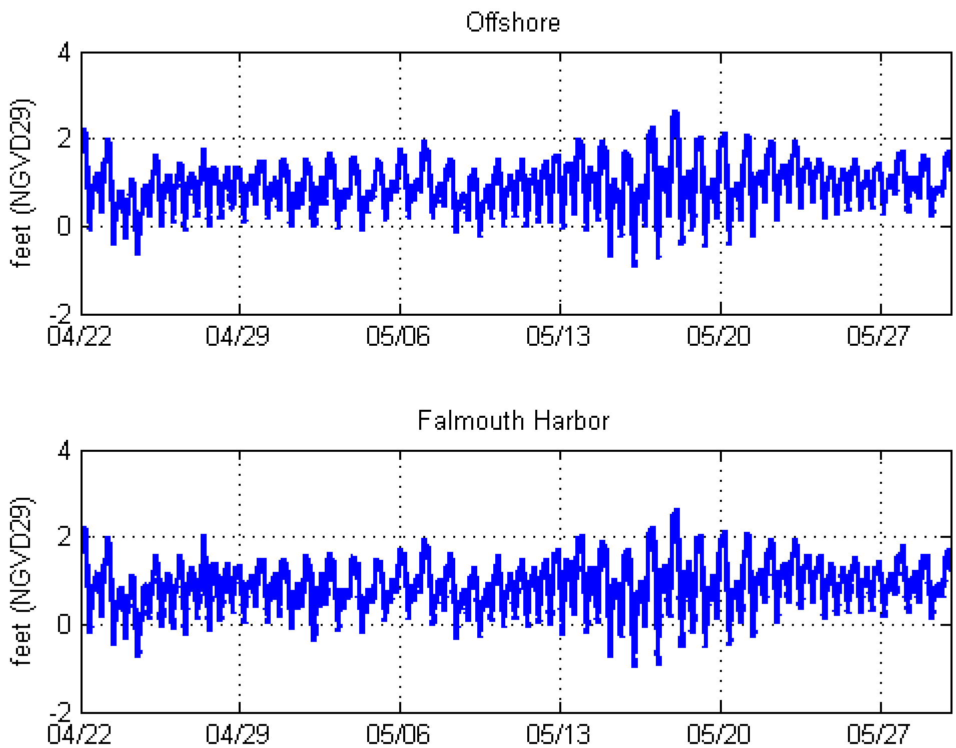

Figure V-4. Water elevation variations as measured at the two locations of the Falmouth Inner Harbor system, from April 22nd to May 30th 2007.

The loss of amplitude together with increasing phase delay with increasing distance from the inlet is described as tidal attenuation. Tide attenuation can be a useful indicator of flushing efficiency in an estuary. Attenuation of the tidal signal is caused by the geomorphology of the near-shore region, where channel restrictions (e.g., bridge abutments) 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 Falmouth Inner Harbor estuary system (Figure V-5), demonstrates no discernable attenuation in the system.

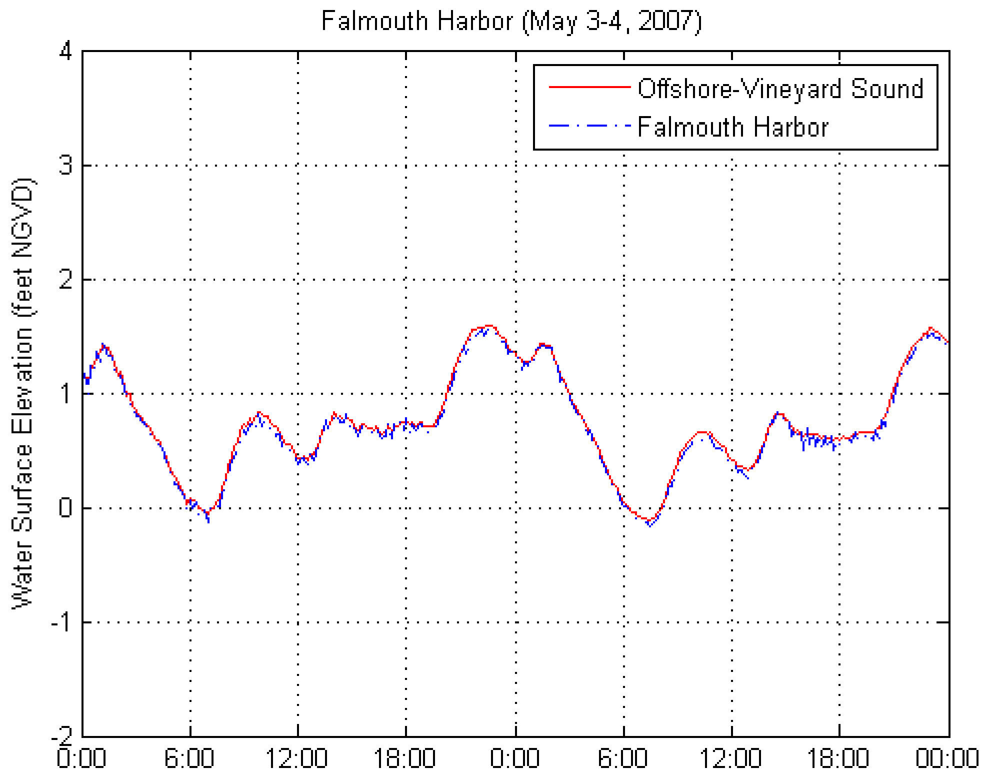

Figure V-5. Plot showing two tide cycles tides at two stations in the Falmouth Inner Harbor system plotted together. Demonstrated in this plot is lack of attenuation in the tidal signal between Vineyard Sound and the upper reach of the Harbor.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 38-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 Vineyard Sound 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 were 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 Falmouth Inner Harbor and Vineyard Sound.

Table V-1. Tide datums computed from records collected in the Falmouth Inner Harbor Estuarine system April 22 - May 30, 2007. Datum elevations are given relative to NGVD29		
Tide Datum	Offshore	Falmouth Inner Harbor
Maximum Tide	3.277	3.223
MHHW	1.906	1.907
MHW	1.545	1.554
MTL	0.822	0.788
MLW	0.100	0.022
MLLW	-0.106	-0.189
Minimum Tide	-0.912	-0.964

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

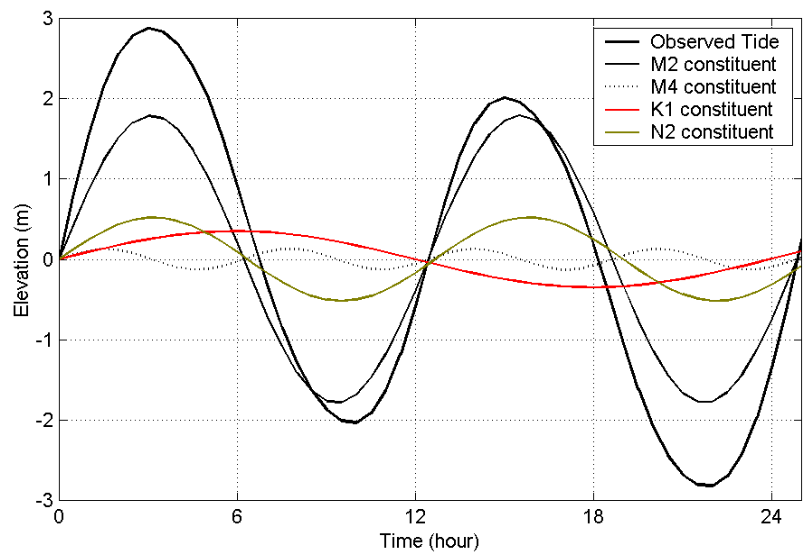

Figure V-6. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

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 change in the M2 amplitude from the offshore station to the Falmouth Inner Harbor station 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 1.0 feet. The diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar) possess amplitudes of approximately 0.57 feet and 0.53 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 Falmouth Inner 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	0.517	0.161	0.057	0.287	0.092	0.225	0.268
Falmouth Inner Harbor	0.521	0.157	0.058	0.286	0.089	0.226	0.269

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 the tide gauge locations, both inside the system and offshore. Because the delay between the two stations is only a little more than two sampling time steps of the tide gauges, this confirms that there is no appreciable attenuation in this system.

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

Location	Delay (minutes)
Falmouth Inner Harbor	23

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 system 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 gauge, with the predicted tide resulting from the harmonic analysis, and the resulting non-tidal residual.

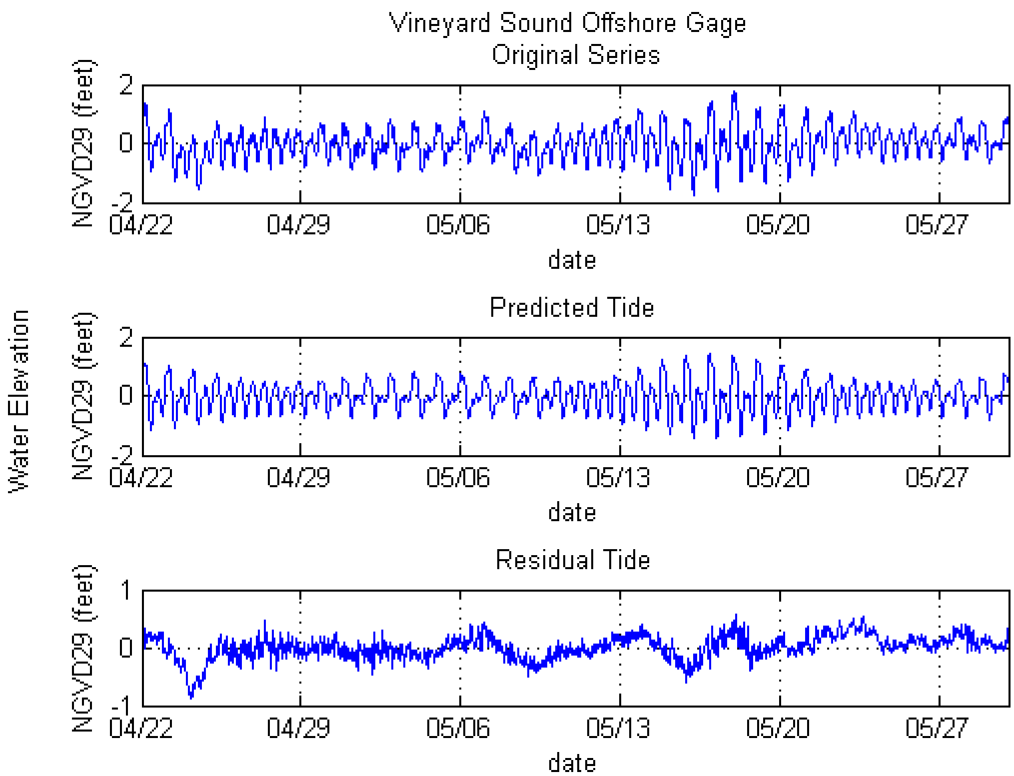

Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured at the Offshore Gage (S-2).

Table V-4 shows that the percentage contribution of tidal energy was the driving force of the observed tidal signal in the Falmouth Inner Harbor Estuarine System. The analysis also shows that tides are responsible for 86% of the water level changes in the system. The remaining 14% 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, Falmouth Inner Harbor, 2007

Location	Total Variance (ft^2)	Total (%)	Tidal (%)	Non-tidal (%)
Offshore	0.290	100	86.3	13.7
Falmouth Inner Harbor	0.294	100	85.7	14.5

The results from Table V-4 indicate that hydrodynamic circulation throughout the Falmouth Inner 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 gauge 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 Falmouth Inner Harbor estuary system. Once calibrated, the model was used to calculate the mean volume of the whole of Falmouth Inner 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 Falmouth Inner 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 gauge location. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several (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 software package. The digital shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary with 837 elements and 2516 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 channel constrictions (e.g., at the inlet) 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 inlet 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 the upper reaches of the Harbor basin. Appropriate implementation of wider node spacing and larger elements reduces computer run time with no sacrifice of accuracy.

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 Vineyard Sound (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 Vineyard Sound 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 Vineyard Sound 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).

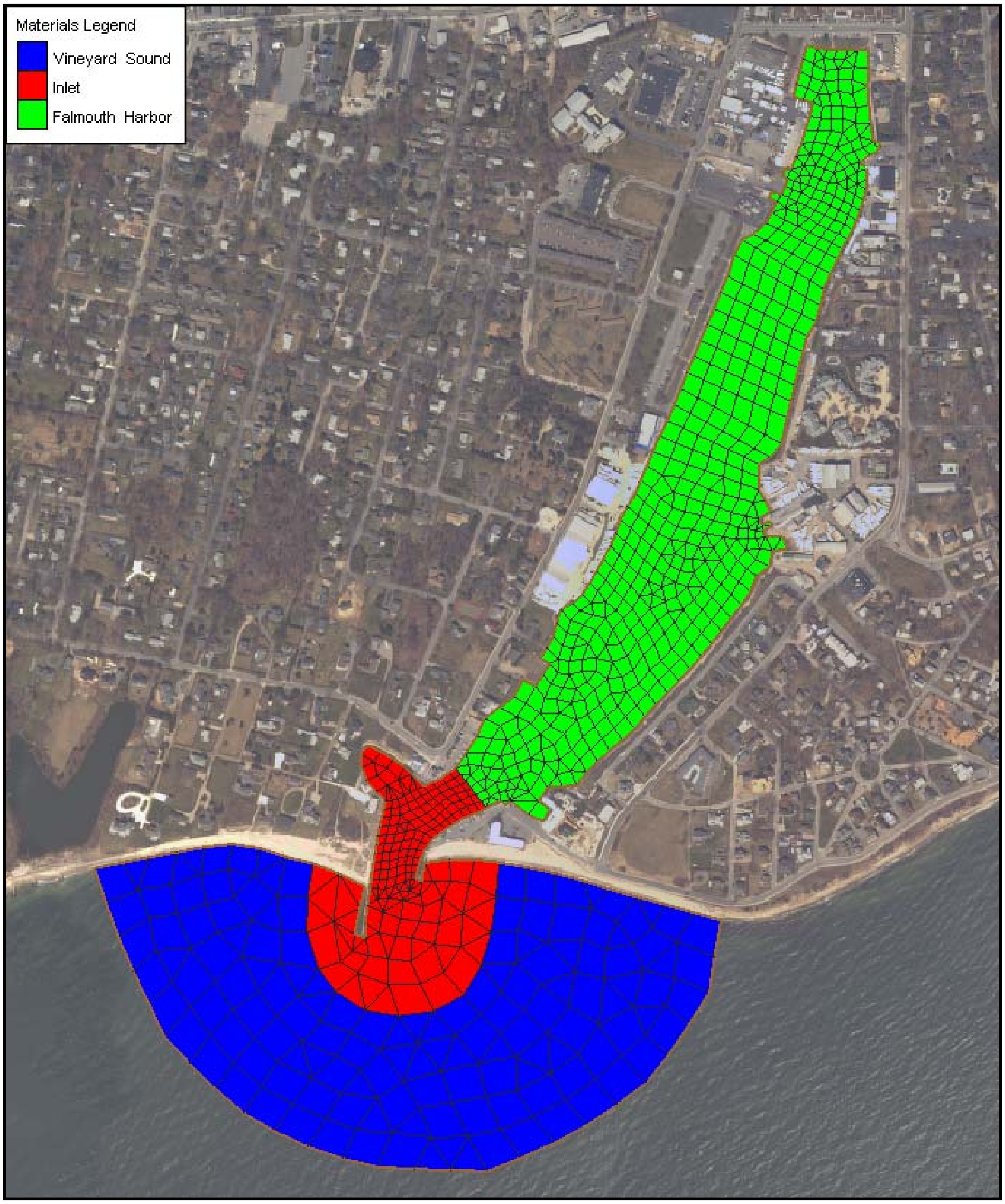

Figure V-8. The model finite element mesh developed for Falmouth Inner Harbor estuary system. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained at the Offshore Gage (S-2).

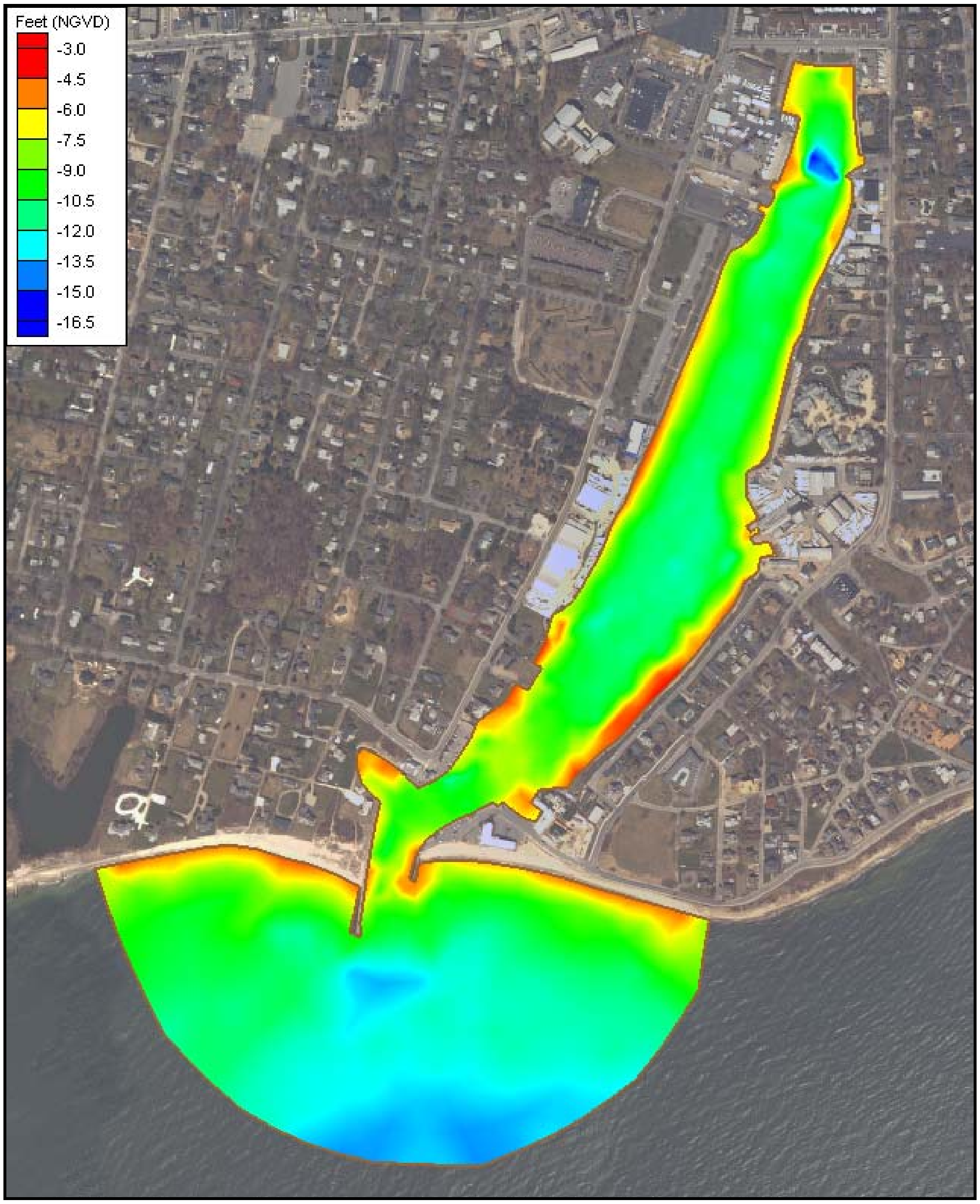

Figure V-9. Depth contours of the completed Falmouth Inner Harbor finite element mesh.

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, 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 gauge station. Initially, the model was calibrated by the visual agreement between modeled and measured tides. To refine the calibration procedure, water elevations were output from the model at the same location in the estuary where a tide gauge was 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 0110 hours EDT May 3, 2007 and ending 0050 hours EDT May 13, 2007. This time period included a 24-hour model spin-up period, and an 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 2.2 feet from minimum low to maximum high tides. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. Modeled tides were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.3.3.1 Friction Coefficients

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

Table V-5. Manning's Roughness coefficients used in simulations of modeled embayments.

Embayment	Bottom Friction
Offshore	0.025
Inlet	0.025
Falmouth Inner 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
Falmouth Inner 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 four gauge locations are presented in Figures V-10 through 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 0.01 feet for all locations, which indicates that the model accurately predicts tidal hydrodynamics within Falmouth Inner Harbor. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the validation 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 39-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 gauges (±0.12 ft). Time lag errors were less than the time increment resolved by the modeled and measured tide data records (1/6 hours or 10 minutes), indicating excellent agreement between the model and data.

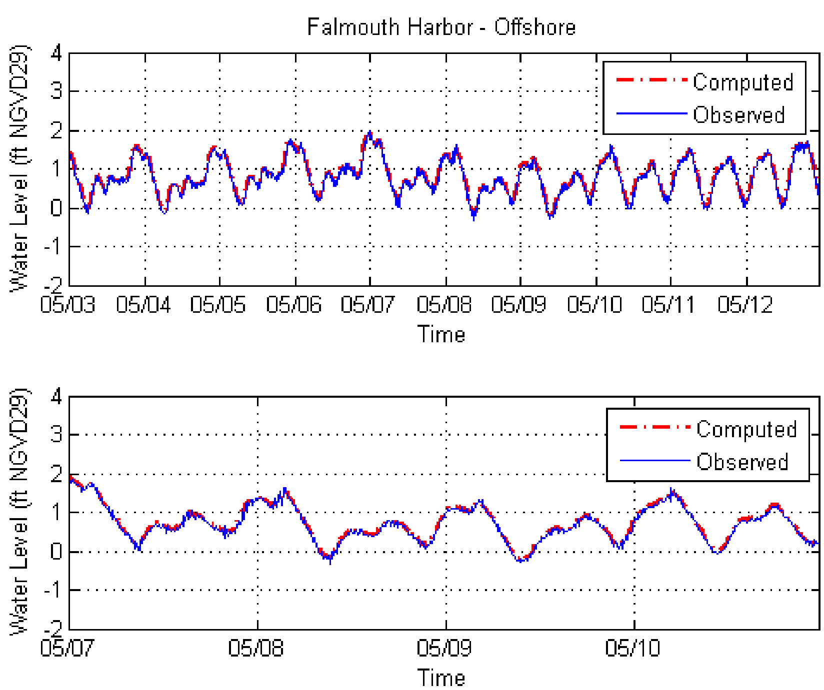

Figure V-10. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the offshore gauge (Vineyard Sound) station. The top plot shows the entire record with the bottom plot showing a 4-day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

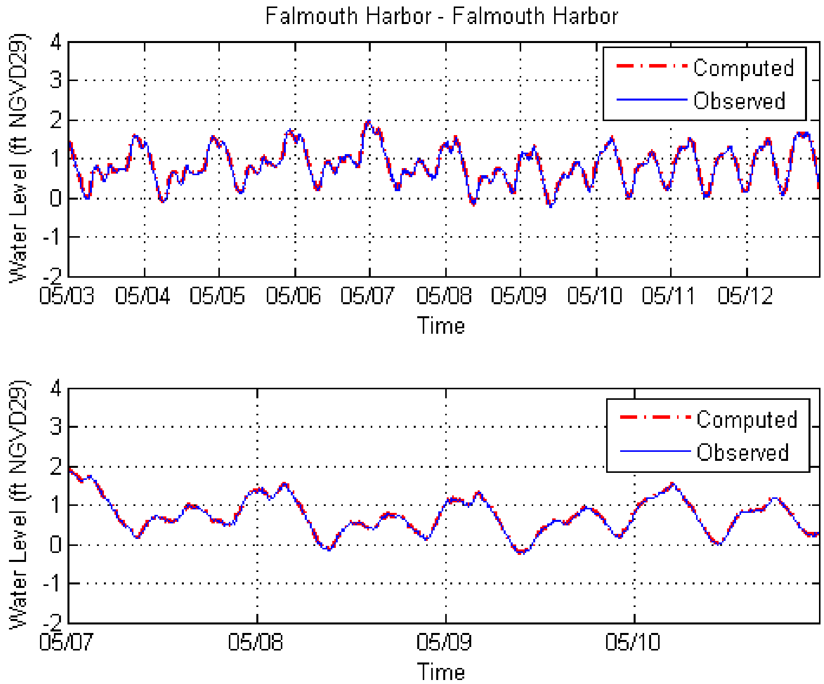

Figure V-11. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Falmouth Inner Harbor Gage Station. The top plot shows the entire record with the bottom plot showing a 4-day segment.

Table V-7. Comparison of Tidal Constituents validated RMA2 model versus measured tidal data for the period May 19 to May 29, 2007.

Model Verification Run						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	N_2	K_1	ΦM_2	ΦM_4
Offshore	0.558	0.156	0.114	0.320	87.8	-11.6
Falmouth Inner Harbor	0.558	0.157	0.115	0.320	88.0	-11.4
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	N_2	K_1	ΦM_2	ΦM_4
Offshore	0.561	0.157	0.116	0.320	86.2	-15.1
Falmouth Inner Harbor	0.558	0.154	0.113	0.321	88.0	-15.5
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	N_2	K_1	ΦM_2	ΦM_4
Offshore	-0.003	-0.001	-0.002	0.000	-3.4	-3.6
Falmouth Inner Harbor	-0.000	0.003	0.002	-0.001	0.0	-4.3

V.3.4 Model Circulation Characteristics

The final calibrated and validated model serves as a useful tool for investigating the circulation characteristics of the Falmouth Inner 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 Falmouth Inner Harbor inlet are slightly larger than velocities during the ebb portion of the tide. Maximum depth-averaged velocities in the model are approximately 0.24 feet/sec for flooding tides, and 0.21 ft/sec for ebbing tides. An example of the 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.

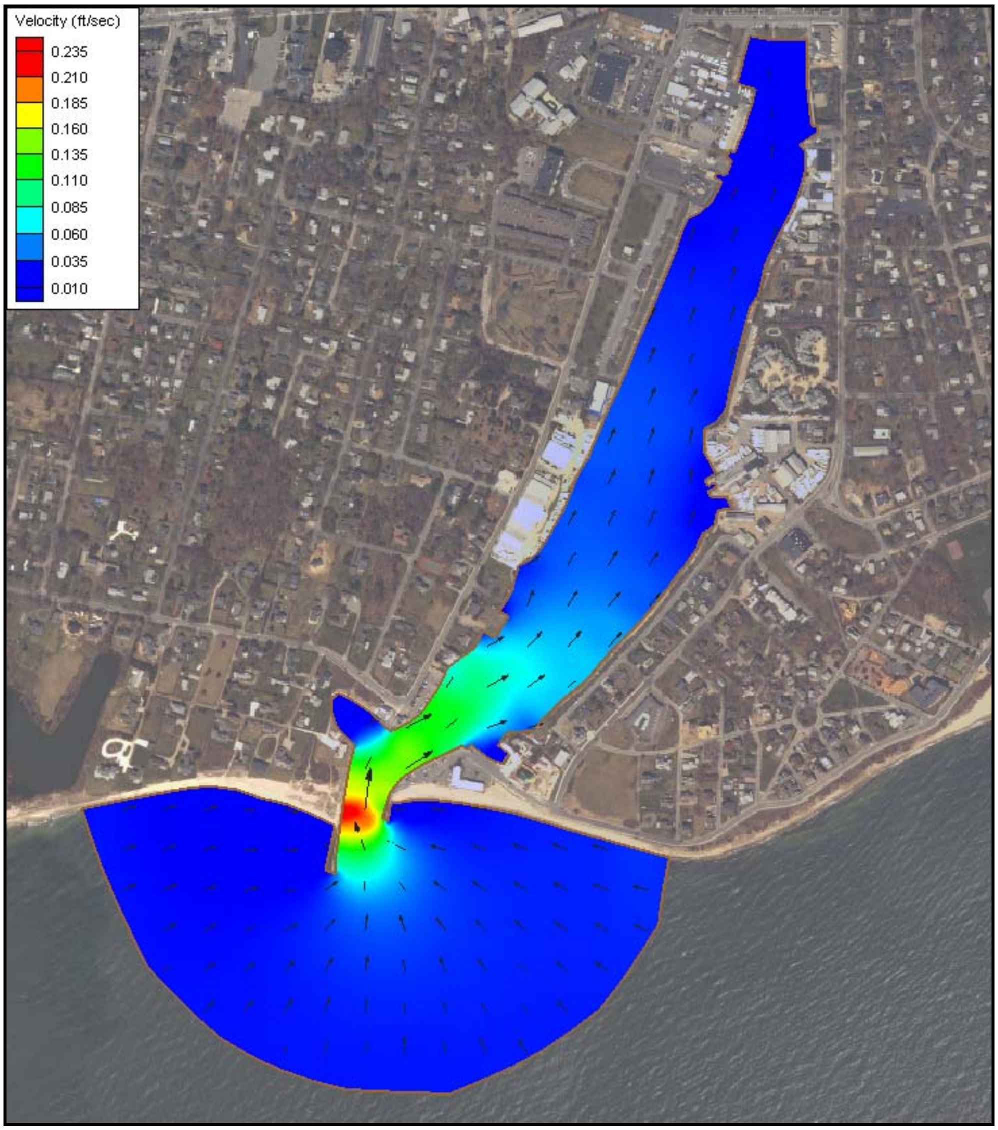

Figure V-12. Example of hydrodynamic model output in Falmouth Inner Harbor for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

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 Falmouth Inner Harbor inlet is seen in Figure V-13. During the simulation time period, maximum modeled flood tide flow rates through the Falmouth Inner Harbor inlet were 266 ft^3/sec and ebb tide flow rates were 211 ft^3/sec.

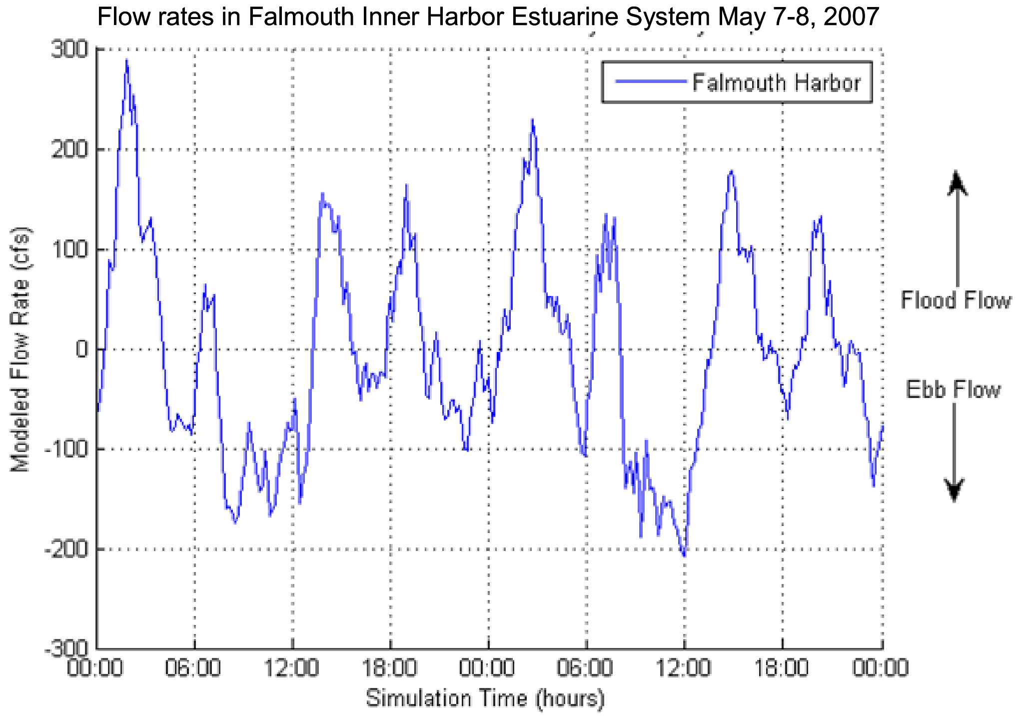

Figure V-13. Time variation of computed flow rates for transects across the Falmouth Inner Harbor Inlet. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are likewise large compared to neap tide conditions. Positive flow indicates 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 Falmouth Inner Harbor is tidal exchange. A rising tide offshore in Vineyard Sound 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 Sound 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 Falmouth Inner Harbor as an example, the system residence time is the average time required for water to migrate from the head of Falmouth Inner Harbor, through the lower portions of the Harbor, and finally into Vineyard Sound, 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). For systems with multiple sub-embayments, 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 Vineyard Sound.

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 Falmouth Inner Harbor.

The volume of the embayment, as well as the respective tidal prism, 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 embayment system.

Table V-8. Mean volumes and average tidal prism of the Falmouth Inner Harbor estuary system during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Falmouth Inner Harbor	14,509,000	1,666,000

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). As the system is comprised on one main basin and not sub-divided into sub-embayments, system and local residence times were equal. Units then were converted to days. The long local residence time (4.5 days) of the whole Falmouth Inner Harbor estuary system shows that the system most likely flushes poorly.

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

Embayment	Local Residence Time (days)	System Residence Time (days)
Falmouth Inner Harbor	4.5	4.5

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 Falmouth Inner 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. In addition, limited topographic measurements were available in some of the smaller sub-embayments of the system.

Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. In this case, the “strong littoral drift” assumption would lead to an under-prediction of residence time. Since littoral drift in Vineyard Sound 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 Falmouth Harbor estuary 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 systems. Files of node locations and node connectivity for the RMA-2V (Vertically Averaged) 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 20-tidal cycle period in May 2007. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28 day spin-up period, to allow the model 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 Falmouth Harbor estuary system, consisting of the background concentrations of total nitrogen in the waters entering from Vineyard Sound. 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. Five years of data (collected between 2006 and 2010) were available for stations monitored by SMAST in the Falmouth Harbor estuary 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 Falmouth Harbor estuary 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 Falmouth Harbor estuary system. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod 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. Town of Falmouth water quality monitoring data, and modeled Nitrogen concentrations for the Falmouth Harbor estuary 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
Upper Harbor	FIH-1	0.588	0.141	74	0.5814	0.5880	0.5848
Lower Harbor	FIH-2	0.533	0.110	85	0.5148	0.5302	0.5233
Lower Harbor	FIH-3	0.496	0.076	75	0.4254	0.4954	0.4677

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.

Figure VI-1. Estuarine water quality monitoring station locations in the Falmouth Harbor estuary system. Station labels correspond to those provided in Table VI-1. The approximate location of the threshold station is depicted by the red symbol (Sentinel), at a location midway between FIH-1 and FIH-2.

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 Falmouth Harbor estuary 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 Falmouth Harbor estuary system was used for the water quality constituent modeling portion of this study.

Based on measured surface water flow rates from SMAST and groundwater recharge rates from the USGS, the hydrodynamic model was set-up to include the latest estimates of flows from Morse Pond (via a culvert emptying into the head of the system). The Morse Pond culvert has a mean measured flow rate of 0.32 ft^3/sec (785.9 m^3/day), which is only 0.9% of the average tidal prism of Falmouth Harbor. The overall groundwater flow rate into the system is 0.94 ft^3/sec (2,301 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 28 day. At the end of the spin-up period, the model was run for an additional 20 tidal-cycle (250 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 Falmouth Harbor estuary 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, 3) summer benthic regeneration, and 4) point source inputs developed from measurements of the freshwater portions of the Morse Pond culvert. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed direct atmospheric deposition loads for Falmouth Harbor were evenly distributed at grid cells that formed the outer edge of the embayment. Benthic regeneration loads were distributed among another sub-set of grid cells which are in the interior portion of each basin.

The loadings used to model present conditions in Falmouth Harbor estuary 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, the primary portion of the total loading rate for the system comes from watershed loads.

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 Vineyard Sound was set at 0.280 mg/L, based on SMAST data from Vineyard Sound. The open boundary total nitrogen concentration represents long-term average summer concentrations found within Vineyard Sound.

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 Falmouth 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 portion of the estuary.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Falmouth Harbor estuary 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)
Upper Harbor	2.573	0.219	0.780
Lower Harbor	3.860	0.219	0.753
Morse Culvert	0.764	-	-

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

Embayment Division	E m^2/sec
Vineyard Sound	1.5
Inlet	0.7
Lower Harbor	0.9
Upper Harbor	0.8

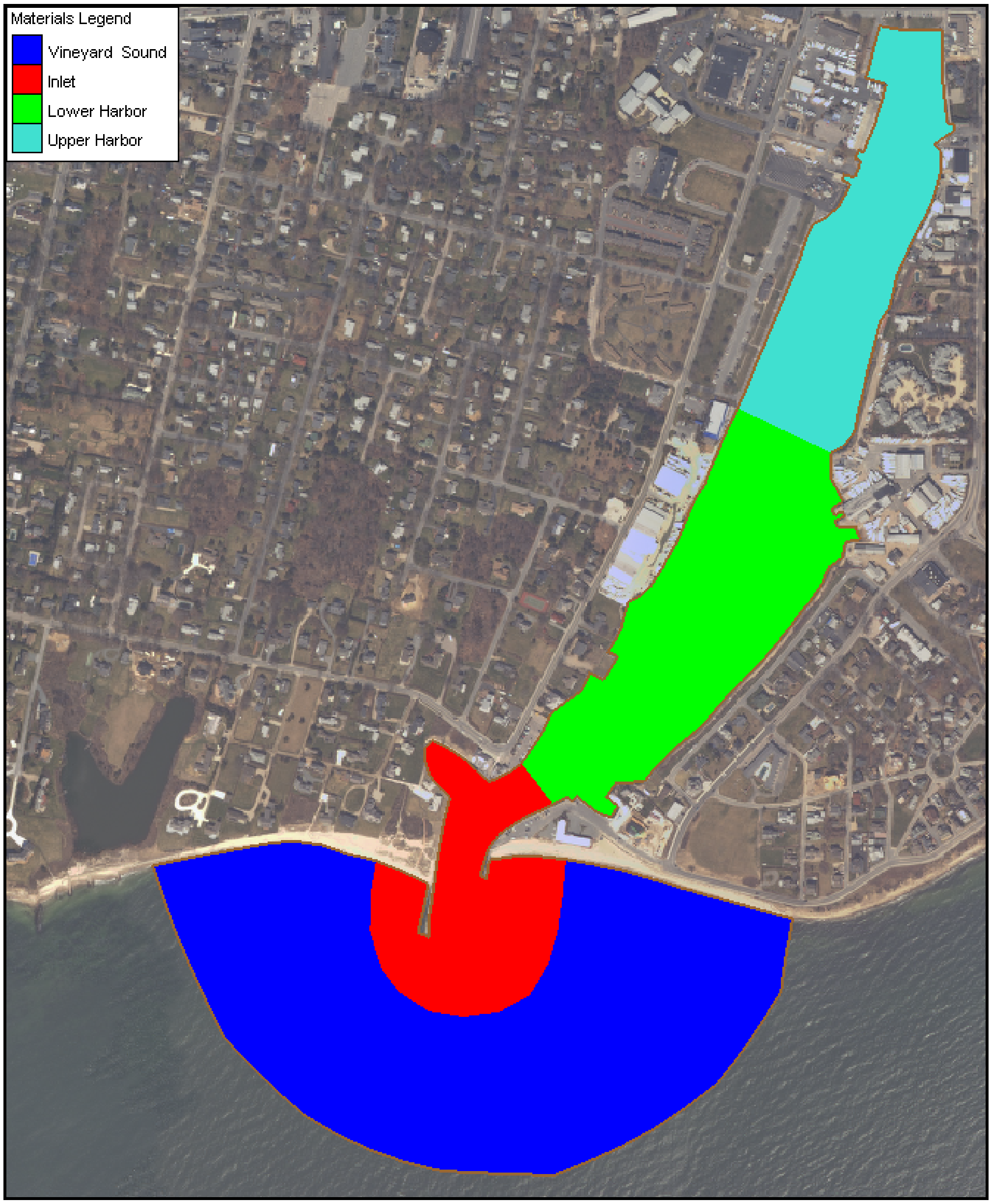

Figure VI-2. Map of the Falmouth Harbor water quality model longitudinal dispersion coefficients. Color patterns designate the different areas used to vary model dispersion coefficient values.

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 one standard deviation 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 verse modeled target values for the system. The model fit is good for the Falmouth Harbor system, with rms error of 0.017 mg/L and an R^2 correlation coefficient of 0.79.

A contour plot of calibrated model output is shown in Figure VI-4 for Falmouth Harbor estuary 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 10-tidal-day model simulation output period.

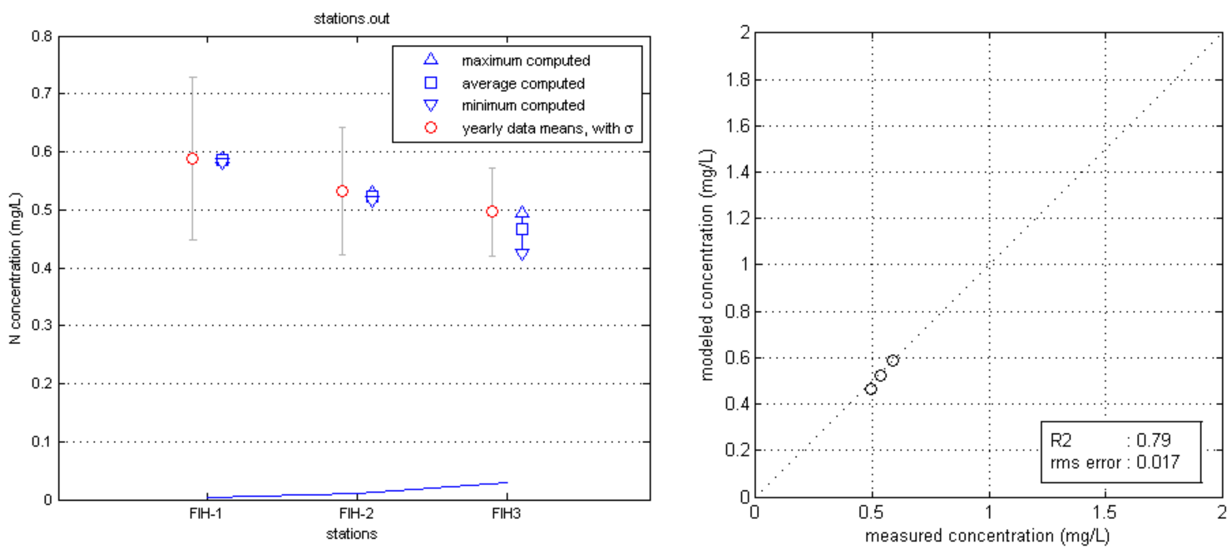

Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Falmouth Harbor estuary system. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed 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 each model are also presented.

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 Falmouth Harbor estuary 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 31.6 ppt. For groundwater inputs, salinities were set at 0 ppt. Groundwater input used for the model was 4.07 ft^3/sec (9,704 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.

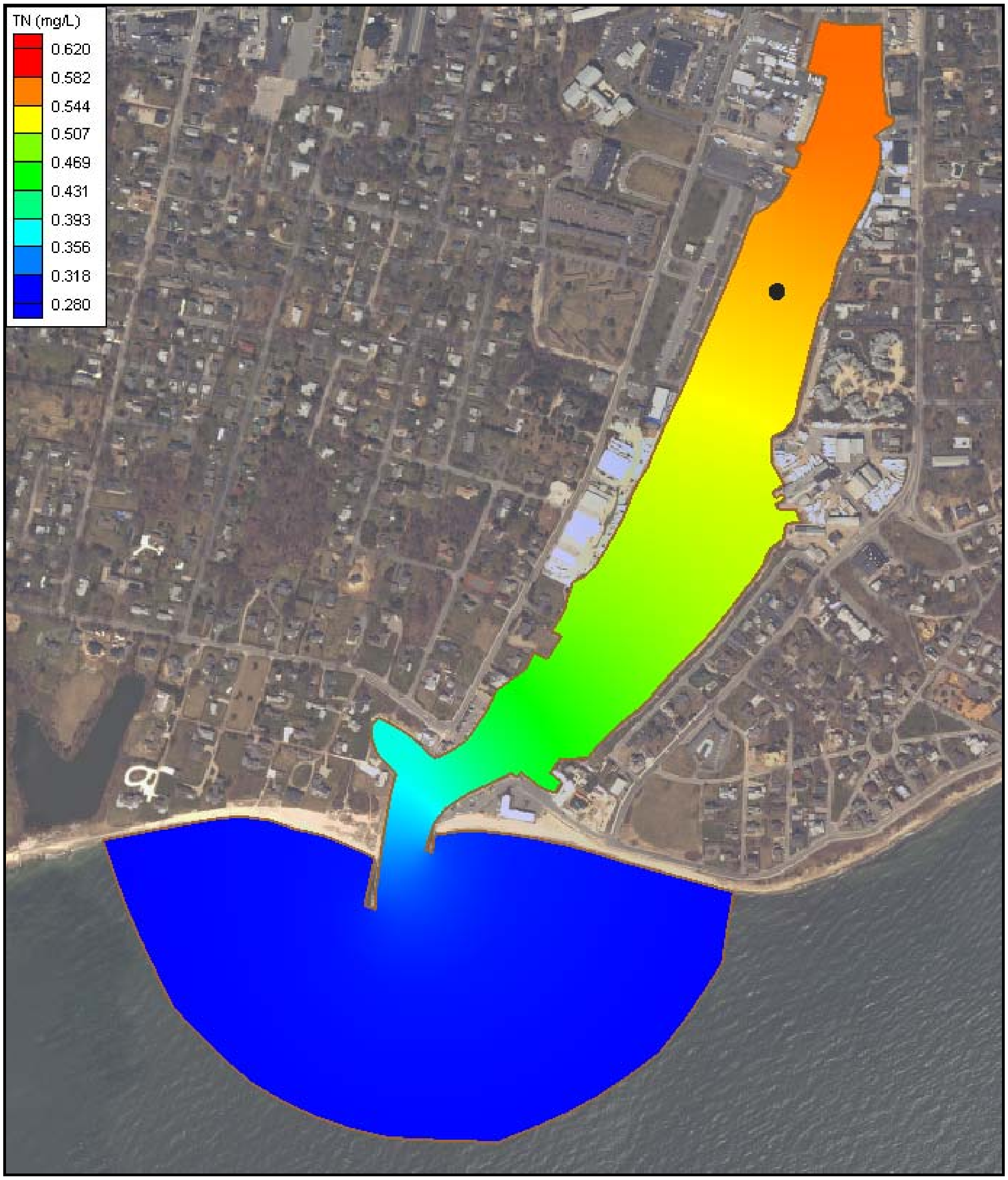

Figure VI-4. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for Falmouth Harbor estuary system. The approximate location of the sentinel threshold stations for Falmouth Harbor estuary system is shown by the black symbol.

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 Falmouth Harbor estuary system. The rms error of the models was 0.160 ppt, and the correlation was 0.85. 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.

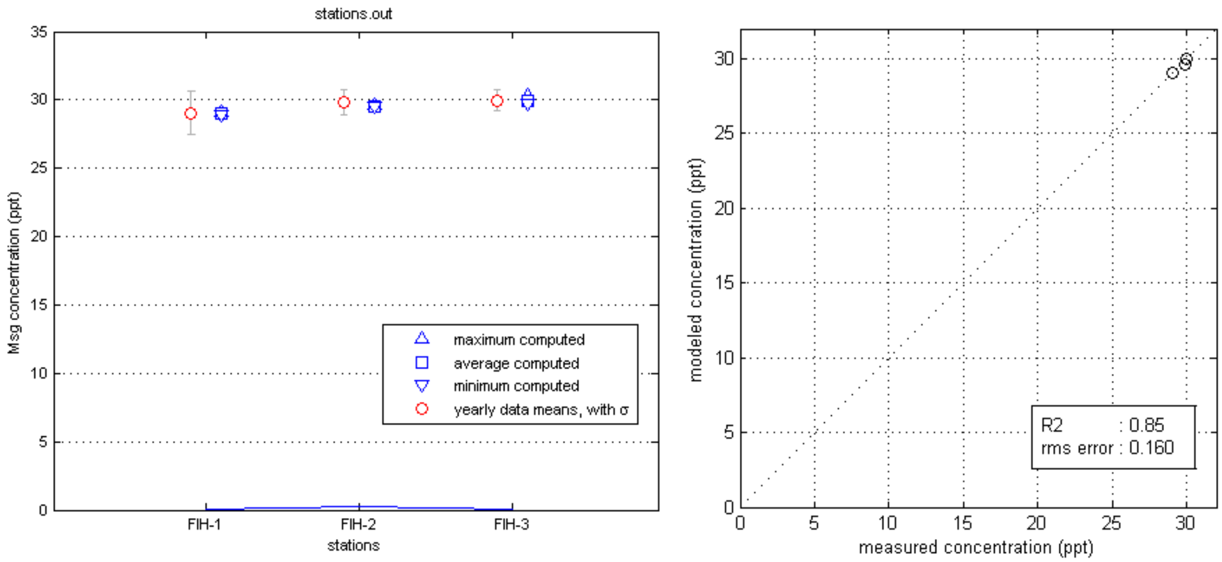

Figure VI-5. Comparison of measured and calibrated model output at stations in Falmouth Harbor estuary system. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation 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.

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.

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 7.9% increase in watershed nitrogen load to Falmouth Harbor as a result of potential future development, with an increase of 26.9% from the Morse Culvert flow. 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 96% for Falmouth Harbor and 80% for the Morse Culvert Flow.

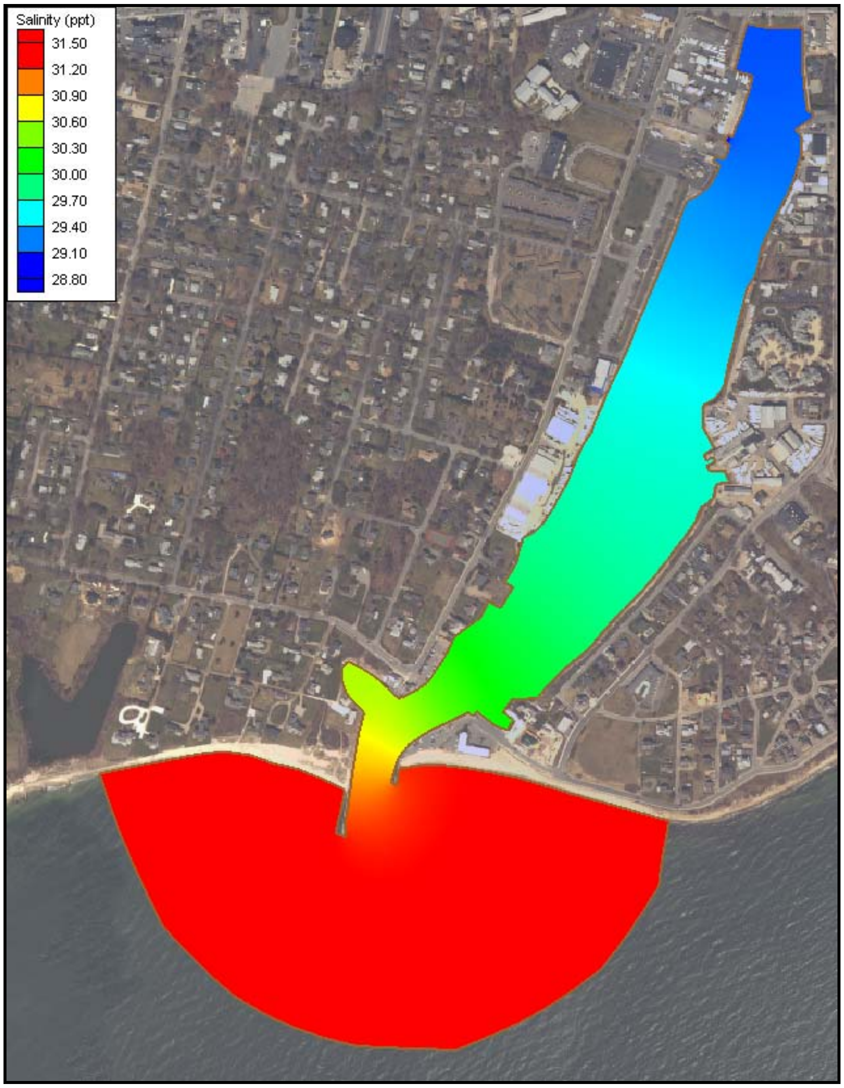

Figure VI-6. Contour plots of modeled salinity (ppt) in Falmouth Harbor estuary system.

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 Falmouth Harbor estuary system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	build out (kg/day)	build out % change	no load (kg/day)	no load % change
Upper Harbor	2.573	2.776	7.9%	0.096	-96.3%
Lower Harbor	3.860	4.164	7.9%	0.145	-96.3%
Morse Culvert	0.764	0.970	26.9%	0.151	-80.3%

For the build-out scenario, a breakdown of the total nitrogen load entering the Falmouth Harbor estuary system sub-embayments is shown in Table VI-5. The benthic flux for the build-out scenarios is assumed to vary proportional to the watershed load, where an increase in watershed load will result in an increase in benthic flux (i.e., a positive change in the absolute value of the flux), and *vise versa*.

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Harbor	2.776	0.219	0.826
Lower Harbor	4.164	0.219	0.793
Morse Culvert	0.970	-	-

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of the Falmouth Harbor estuary system was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Vineyard Sound) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most at the head of the system (4.7%), while the change was less noticeable near the inlet (3.4%). 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. For typical systems, a total nitrogen concentration greater than 0.5 mg/L leads to negative impacts in benthic fauna.

Table VI-6. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Falmouth Harbor estuary system. The sentinel threshold station is in bold print.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Upper Harbor	FIH-1	0.5848	0.6125	4.74%
Upper Harbor*	**Sentinel**	**0.5541**	**0.5785**	**4.40%**
Lower Harbor	FIH-2	0.5233	0.5445	4.05%
Lower Harbor	FIH-3	0.4677	0.4838	3.44%

* The sentinel threshold station was derived by taking the average of stations FIH-1 and FIH-2

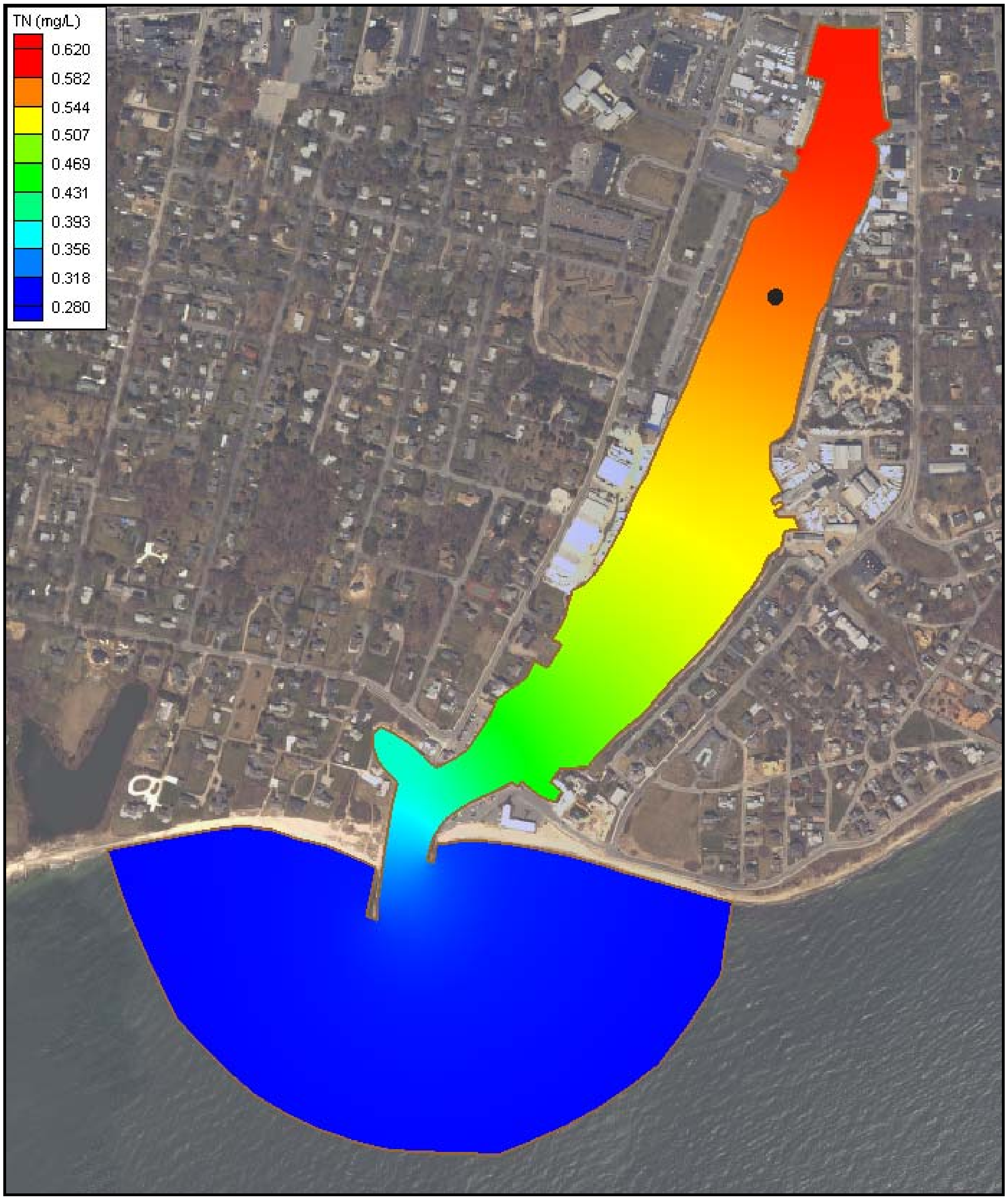

Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in Falmouth Harbor estuary system, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold stations for Falmouth Harbor estuary system is shown by the black symbol.

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 Falmouth Harbor estuary system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Harbor	0.096	0.219	0.337
Lower Harbor	0.145	0.219	0.396
Morse Culvert	0.151	-	-

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Again, total nitrogen concentrations in the receiving waters (i.e., Vineyard Sound) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from “no load” was significant as shown in Table VI-8, with reductions of over 32%. 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 Falmouth Harbor estuary system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions).

Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Upper Harbor	FIH-1	0.5848	0.3427	-41.4%
Upper Harbor*	**Sentinel**	**0.5541**	**0.3363**	**-39.31%**
Lower Harbor	FIH-2	0.5233	0.3298	-37.0%
Lower Harbor	FIH-3	0.4677	0.3180	-32.0%

* The sentinel threshold station was derived by taking the average of stations FIH-1 and FIH-2

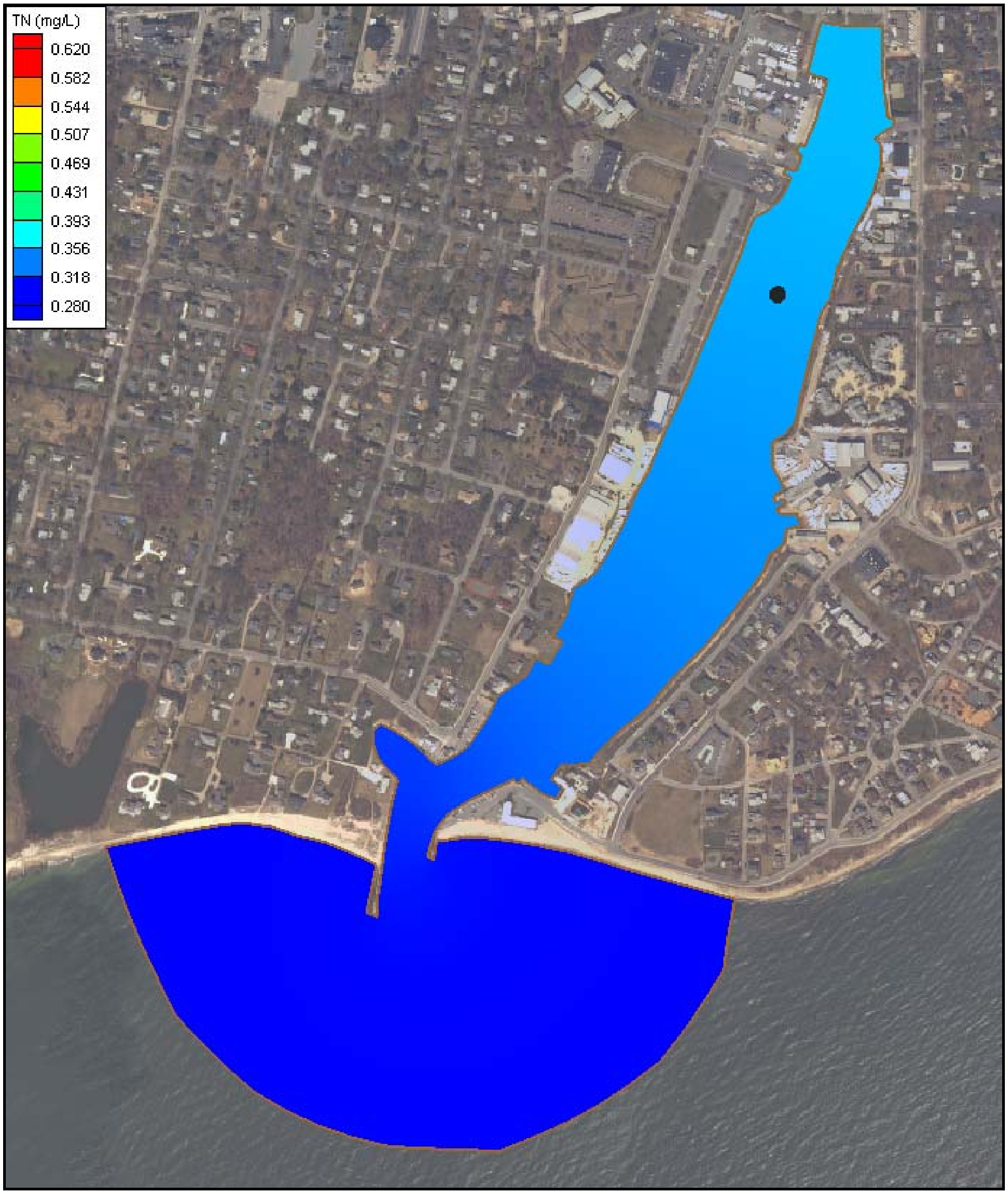

Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in Falmouth Harbor estuary system, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold stations for Falmouth Harbor estuary system is shown by the black symbol.

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 Falmouth Inner Harbor embayment system in the Town of Falmouth, MA, our assessment is based upon data from the water quality monitoring database developed by the Coastal Systems Program – SMAST (2006-2009), surveys of eelgrass distribution (1951, 1995, 2001, 2006), benthic animal communities (fall 2007), sediment characteristics (summer 2007), and dissolved oxygen records (summer 2007). 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 (Chapter 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 Vineyard Sound. Falmouth Inner Harbor is an artificial open water embayment, created by permanently opening a coastal freshwater pond to tidal flows from Vineyard Sound. Now after a century of tidal exchanges, Falmouth Inner Harbor has evolved into a fully functioning estuary, supporting important marine resources (benthic invertebrate animal communities, fish and shellfish) and associated uses. As Falmouth Inner Harbor is presently functioning as an open water embayment, it should be managed as such.

As an embayment system, Falmouth Inner Harbor is altered by terrestrial nitrogen inputs, typically resulting from increased nitrogen loading to its watershed and associated with shifts in land-use. Harbor waters have become nitrogen enriched, as the watershed has approached full development (Build-Out). At its present level of nitrogen enrichment the embayment is unable to assimilate additional nitrogen loading without habitat impairments. Also, as reduction in tidal exchange increases the sensitivity of embayment systems to impacts from nitrogen loads, it is important for the management of this estuary that the inlet be maintained at full efficiency. The following assessment is based upon present watershed nitrogen loads and existing tidal exchange.

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 Falmouth Inner Harbor at two (2) locations representative of the dissolved oxygen conditions at the upper reach of the inner basin and the upper reach of the lower basin (Figure VII-1). The dissolved oxygen moorings were deployed to capture 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 Falmouth Inner 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 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. It appears that Falmouth Inner Harbor presently or historically has not supported significant eelgrass beds. It is likely that this is due in part to the artificial nature of this open water embayment that was formed by opening a coastal freshwater pond to tidal exchange to create a protected harbor for boats with continuing modifications of over the past century (initial opening 1907). Therefore, eelgrass habitat was not used as an indicator in the MEP assessment for these systems. Analysis of inorganic N/P molar ratios within the water column of Falmouth Inner Harbor supports this contention that nitrogen is the nutrient to be managed as the ratio in Falmouth Inner Harbor (9) is clearly below the Redfield Ratio value (16) indicating that nitrogen additions will increase phytoplankton production in this system. Within the Falmouth Inner Harbor system, temporal changes in eelgrass distribution could not provide a basis for evaluating recent increases (nitrogen loading) or decreases in nutrient enrichment as there has never been any significant identifiable eelgrass beds (1951, 1995, 2001 and 2006 MassDEP analysis). As a result, nutrient threshold determination was based on results from the dissolved oxygen and chlorophyll mooring data, water quality monitoring results, macroalgae surveys, as well as the benthic infaunal community characterization.

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

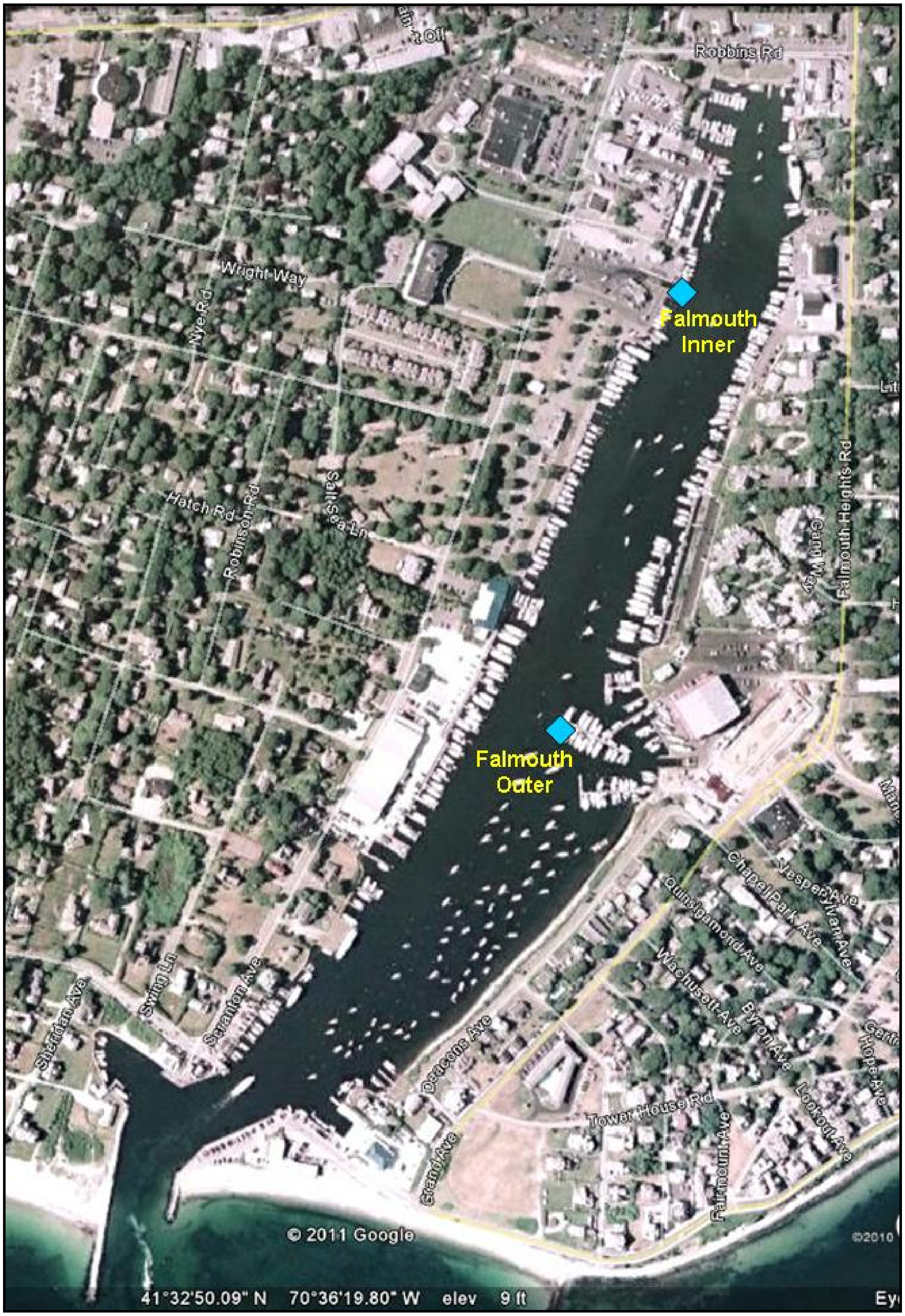

Figure VII-1. Aerial Photograph of the Falmouth Inner Harbor system in the Town of Falmouth showing the location of the continuously recording Dissolved Oxygen / Chlorophyll-a sensors deployed during the Summer of 2007.

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}. Class SB waters must maintain oxygen levels above mg L^{-1}. The tidal waters of the Falmouth Inner Harbor embayment are currently listed under this Classification as SB. Class SB waters are designated as a habitat for fish, other aquatic life and wildlife, including for their reproduction, migration, growth and other critical functions, and for primary and secondary contact recreation. In certain waters, habitat for fish, other aquatic life and wildlife may include, but is not limited to, seagrass. Where designated in the tables to 314 CMR 4.00 for shellfishing, these waters shall be suitable for shellfish harvesting with depuration (Restricted and Conditionally Restricted Shellfish Areas). These waters shall have consistently good aesthetic value. 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 TMDL's 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 of Falmouth'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 Falmouth Inner 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 25-30 days within the interval from July through mid-September. All of the mooring data from the Falmouth Inner Harbor system were collected during the summer of 2007. These data are supplemented by the traditional "grab" sampling data from the water quality monitoring program, which collected bottom water oxygen readings on ~30 dates during the summer period and over several years.

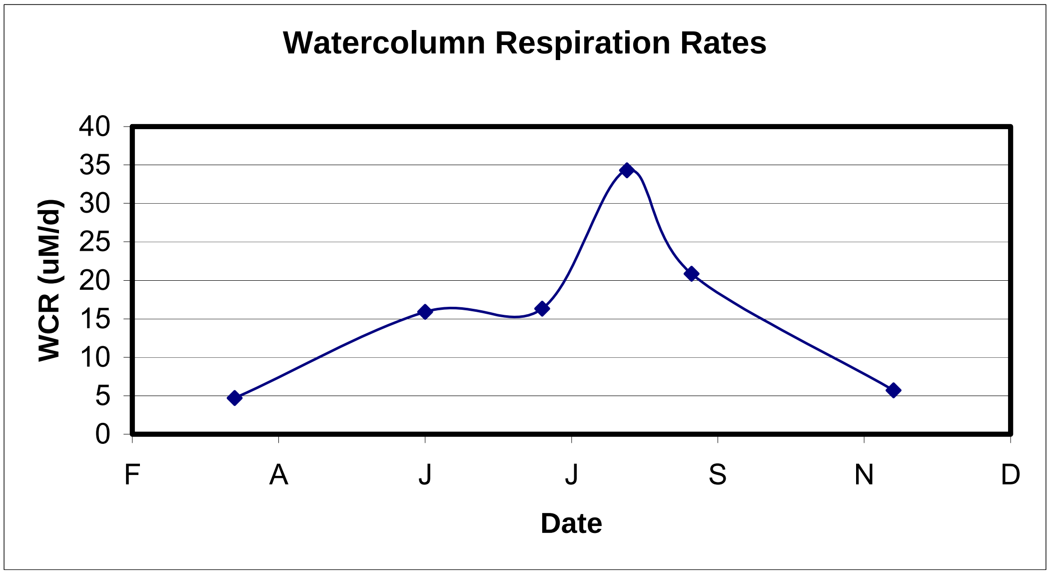

Figure VII-2. Example of typical average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System, Cape Cod (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter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

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

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 50 day deployment periods (Falmouth Harbor-inner and outer) that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate that both the inner and outer portions of the Falmouth Inner Harbor system are showing signs of moderately nutrient enriched waters. The dissolved oxygen data are further described below and depicted in Figures VII-3 and VII-5). The oxygen data are consistent with organic matter enrichment, 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 watershed based nitrogen enrichment of the Falmouth Inner Harbor estuarine system.

The oxygen records for both instrument moorings (inner and outer locations) within Falmouth Inner Harbor show levels of oxygen depletion consistent with the nitrogen enriched condition of harbor waters. The oxygen record from the inner basin has large daily oxygen excursions, ~3 mg L^{-1}. 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 common occurrence of oxygen depletion (<5 mg L^{-1}), evidence of oxygen levels above atmospheric equilibration and the large diurnal excursions support the assessment that the innermost reach of this system is nitrogen over-enriched. The extent of dissolved oxygen depletion indicates that the upper basin of the Falmouth Inner Harbor system is presently experiencing moderate oxygen stress and is consistent with the high chlorophyll levels bordering on eutrophic conditions. The lower basin shows a similar pattern of oxygen depletion and elevated chlorophyll-*a*, but conditions are indicative of less nitrogen enriched waters. This is likely the result of a greater influence of tidal exchange with the high quality waters of Vineyard Sound, compared to the upper basin. While the lower basin also had significant oxygen depletion the extent and duration were less than the upper station. However, there was little difference between chlorophyll-*a* between the basins. It is clear from the oxygen and chlorophyll-*a* measurements that most of Falmouth Inner Harbor is nitrogen enriched and beyond its ability to assimilate additional nitrogen without impairment. The embayment specific results are as follows:

Falmouth Harbor-outer DO/CHLA Mooring (Figures VII-3 and VII-4):

Two moorings were deployed in the Falmouth Harbor system, with one located at the upper margin of the outer basin, near the main marina area. The mooring was centrally located within the overall Harbor tidal reach. Oxygen concentrations generally ranged between 5 and 8 mg L^{-1} and rarely exceed air equilibration (over 8 mg L^{-1}), with levels declining to <5 mg L-1 8% of the time. Moreover, oxygen levels periodically dropped below 5 mg L^{-1} but only rarely dropped to slightly hypoxic conditions where levels approach 4 mg L^{-1} (Figure VII-3, Table VII-1). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. These low to moderate oxygen levels likely result from the high oxygen demand of the organic enriched waters of the outer harbor basin (chlorophyll averages > 10 ug L^{-1}) coupled with twice daily flushing with oxygen rich waters of Vineyard Sound. Despite the only moderate levels of oxygen depletion, there are signs of organic enrichment in this portion of the system as demonstrated by the high measured chlorophyll levels observed during the deployment period. Over the 50 day deployment there did appear to be significant phytoplankton blooms. Chlorophyll-a regularly remained between 10-20 ug L^{-1} and occasionally increased to 30 ug L^{-1}. The levels of oxygen observed in this system is indicative of an embayment basin moderately impaired by nitrogen enrichment, consistent with the high chlorophyll-*a* levels (mooring chlorophyll-*a* average 13.5 ug L^{-1}; monitoring program averages 14-19 ug L^{-1}). In this somewhat open portion of the Falmouth Inner Harbor system, chlorophyll-*a* exceeded the 10 ug L^{-1} benchmark 65 percent of the time (Table VII-2, Figure VII-4). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

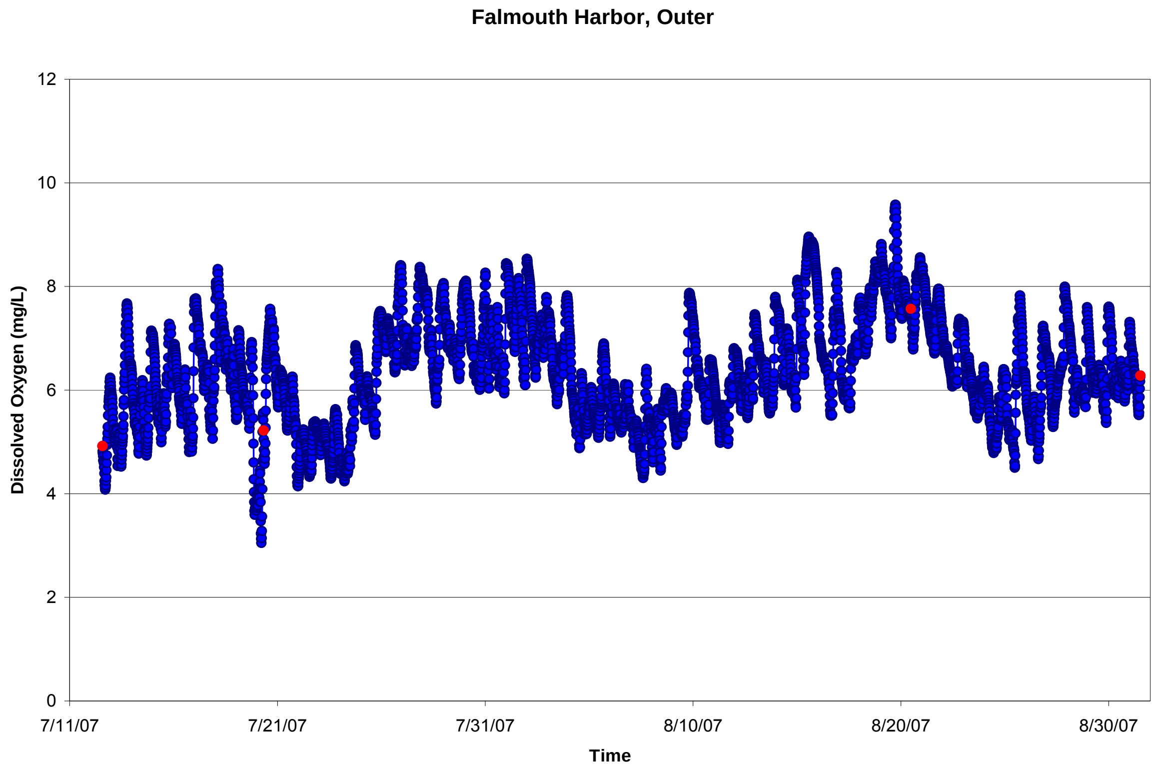

Figure VII-3. Bottom water record of dissolved oxygen at the Falmouth Harbor-outer station, Summer 2007. Calibration samples represented as red dots.

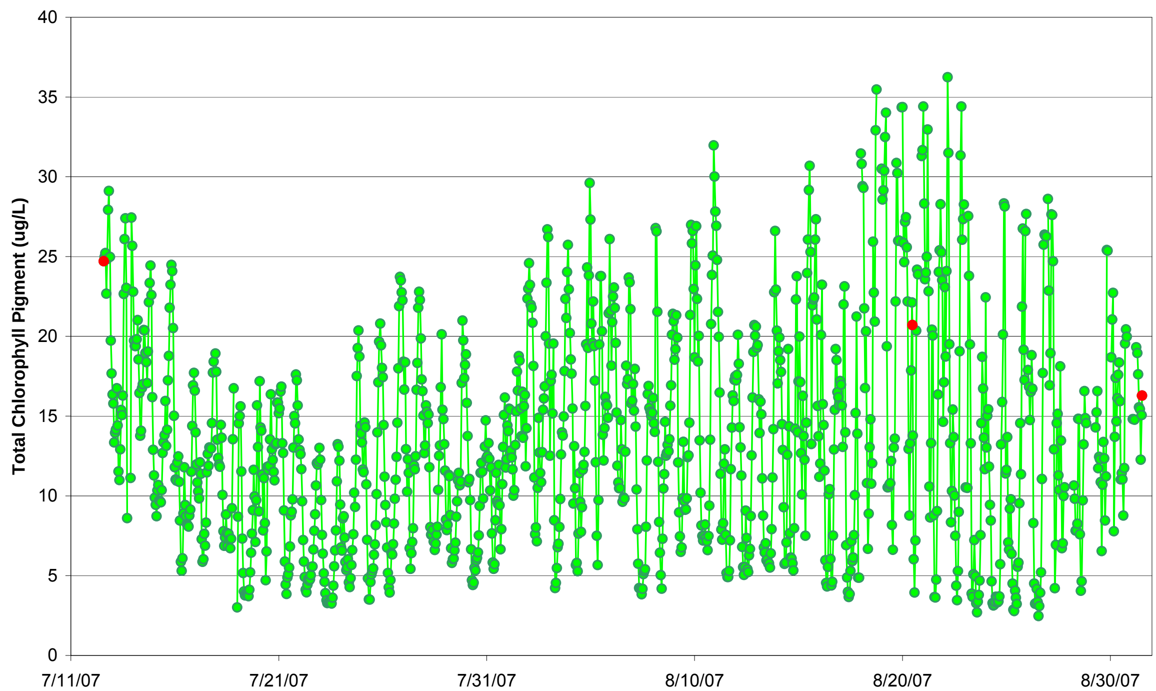

Figure VII-4. Bottom water record of Chlorophyll-*a* in the Falmouth Harbor-outer station, Summer 2007. Calibration samples represented as red dots.

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 Falmouth Inner 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)
Falmouth Harbor Inner	**7/12/2007**	**8/31/2007**	**50.0**	**59%**	**28%**	**3%**	**0%**
			Mean	0.59	0.35	0.16	NA
			Min	0.01	0.01	0.02	0.00
			Max	4.75	3.84	0.32	0.00
			S.D.	0.94	0.66	0.12	NA
Falmouth Harbor Outer	**7/12/2007**	**8/31/2007**	**49.9**	**38%**	**8%**	**1%**	**0%**
			Mean	0.29	0.13	0.11	NA
			Min	0.01	0.01	0.05	0.00
			Max	2.95	0.57	0.19	0.00
			S.D.	0.41	0.15	0.07	NA

Table VII-2. Duration (days and % of deployment time) that chlorophyll-*a* levels exceed various benchmark levels within the Falmouth Inner 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)
Falmouth Harbor, Inner	**7/12/2007**	**8/31/2007**	**49.63**	**92%**	**57%**	**31%**	**14%**	**3%**
Mean Chl Value = 12.4 ug/L			**Mean**	1.63	0.57	0.27	0.19	0.11
			Min	0.04	0.04	0.04	0.04	0.04
			Max	22.13	8.29	1.04	0.63	0.33
			S.D.	4.33	1.28	0.25	0.16	0.08
Falmouth Harbor, Outer	**7/12/2007**	**8/31/2007**	**47.83**	**91%**	**65%**	**37%**	**18%**	**7%**
Mean Chl Value = 13.5 ug/L			**Mean**	1.45	0.41	0.21	0.14	0.11
			Min	0.04	0.04	0.04	0.04	0.04
			Max	6.04	1.17	0.54	0.54	0.33
			S.D.	1.55	0.30	0.15	0.11	0.07

Falmouth Harbor-inner DO/CHLA Mooring (Figures VII-5 and VII-6):

The second of the two instrument moorings deployed in the Falmouth Inner Harbor system was located toward the western side of the central region of the inner basin, well away from the inlet connecting the estuary with the high quality waters of Vineyard Sound. Oxygen conditions within the inner basin clearly indicated a greater level of nitrogen enrichment and higher oxygen related stress compared to the outer basin. Oxygen conditions within the inner basin exhibited large daily excursions in oxygen levels (~3 mg L^{-1}). Oxygen concentrations ranged from levels clearly above (over 8 mg L^{-1}) air equilibration to hypoxic conditions where levels decline to <4 mg L^{-1} (Figure VII-5, Table VII-1). Oxygen measurements by the water quality monitoring program found oxygen depletion to <3 mg L^{-1} and to <4 mg L^{-1} on 10% of the sampling dates. 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 several large algal blooms that were observed during the meter deployment period as well as the high rates of photosynthesis (carbon fixation) and the rapid declines in oxygen after sunset stemming from respiration.

Oxygen levels also showed large daily excursions indicative of high levels of phytoplankton biomass, periodically exceeding 8 mg L^{-1} (mostly towards the middle part of August) and approaching 10 mg L^{-1}. These high oxygen levels are likely the result of the combined effects of photosynthesis primarily by phytoplankton and relatively quiescent waters in the upper part of the system furthest away from the inlet. Over the 50 day deployment there appear to be multiple intense phytoplankton blooms where chlorophyll-*a* regularly increased to 15-20 ug L^{-1} and a few periods of bloom activity where chlorophyll-*a* concentrations were between 20 and 25 ug L^{-1}. The periodic low levels of oxygen observed in this system is indicative of moderate habitat impairment, consistent with the elevated chlorophyll-*a* levels, and also indicative of nitrogen enrichment (mooring chlorophyll-*a* average 12.4 ug L^{-1}; monitoring program averages 19-21 ug L^{-1}) . In the uppermost reaches of the Falmouth Inner Harbor system, chlorophyll-*a* exceeded the 10 ug L^{-1} benchmark 57 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.

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass distribution and analysis of historical data was conducted for the Falmouth Inner Harbor Embayment System by the MassDEP Eelgrass Mapping Program as part of the MEP technical effort. Field surveys of the Harbor were conducted in 1995 and 2001 by MassDEP, as part of this program, with additional observations during summer and fall 2007 by the SMAST/MEP Technical Team. Analysis of available aerial photography from 1951 was conducted to reconstruct the eelgrass distribution prior to the present level of development of the watershed. 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) 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. This temporal information can be used to determine the stability of the eelgrass community in many systems.

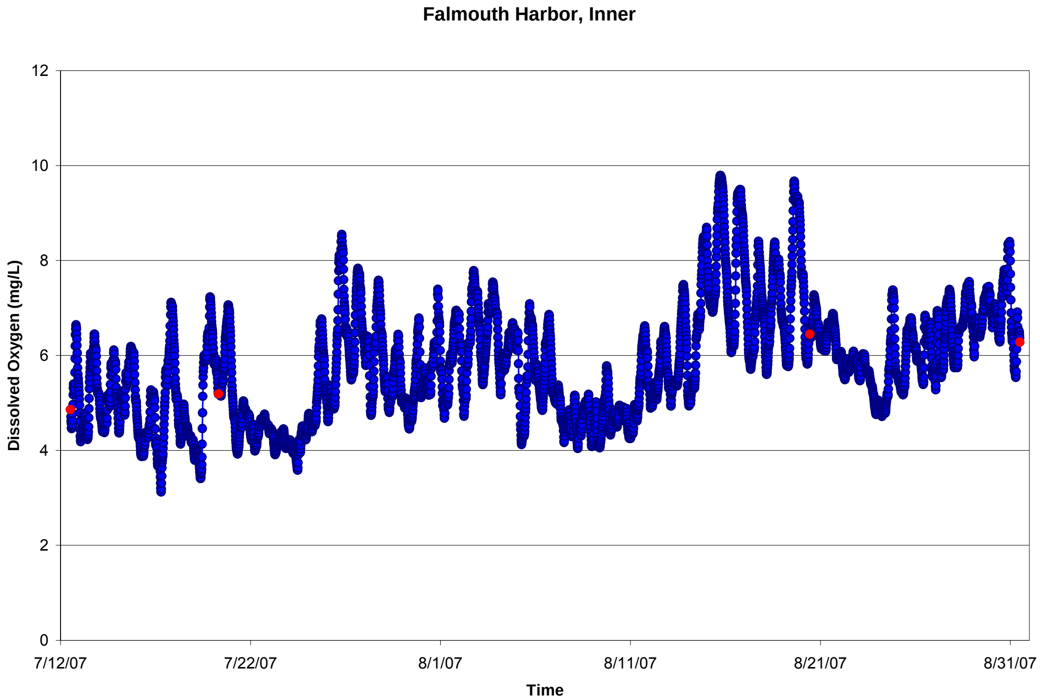

Figure VII-5. Bottom water record of dissolved oxygen at the Falmouth Harbor-inner station, Summer 2007. Calibration samples represented as red dots.

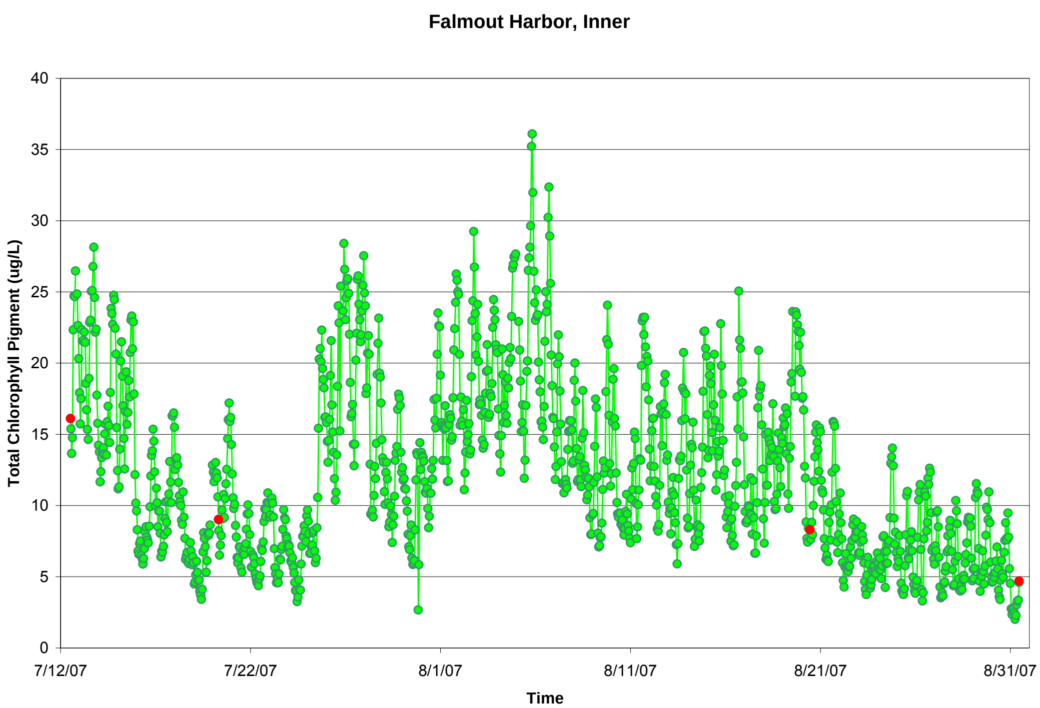

Figure VII-6. Bottom water record of Chlorophyll-*a* in the Falmouth Harbor-inner station, Summer 2007. Calibration samples represented as red dots.

All of the available information on eelgrass relative to this heavily altered embayment system indicates that this embayment has not supported eelgrass over the past half century. The key underlying cause of the absence of historic eelgrass coverage in Falmouth Inner Harbor is its development as an artificial embayment significantly altered by human activity over the past approximately 100 years. The Harbor was formed by opening a fresh pond, Deacon's Pond, in 1907 to create a protected harbor for boats. Human activity gradually altered the now tidal basin into today's deeper open water embayment system. In addition, as a result of the armoring of its shoreline, the basin does not presently support any significant fringing tidal marsh along its shores. The MassDEP analysis that eelgrass beds were not present within the Falmouth Inner Harbor system in 1951, 1995 or 2001 is consistent with the history of alteration of the system and its present level of nitrogen related water quality.

As eelgrass beds could not be documented to exist, either historically or presently, within the basins of Falmouth Inner Harbor, the thresholds analysis for this system is necessarily focused on restoration of impaired benthic infaunal animal habitat. However, it is likely that nitrogen management within this will improve eelgrass habitat within the down-gradient near shore waters of Vineyard Sound. This down-gradient effect, to the extent that it occurs, will be a by-product of the restoration and was not part of the thresholds analyses for Falmouth Inner Harbor.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 6 locations within the Falmouth Inner Harbor Embayment System (Figure VII-7), 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 while it is clear that Falmouth Inner Harbor has never supported significant eelgrass beds in the past century and while it is showing signs based on DO and chlorophyll-*a* levels of moderate impairment from nutrient enrichment, it is possible to improve habitat conditions to at least be supportive of healthy benthic communities. 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 (moderately impaired→significantly impaired→severely degraded) and what nutrient concentrations would be supportive of healthy habitat. This assessment is also important for the establishment of site-specific nitrogen thresholds (Section VIII).

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

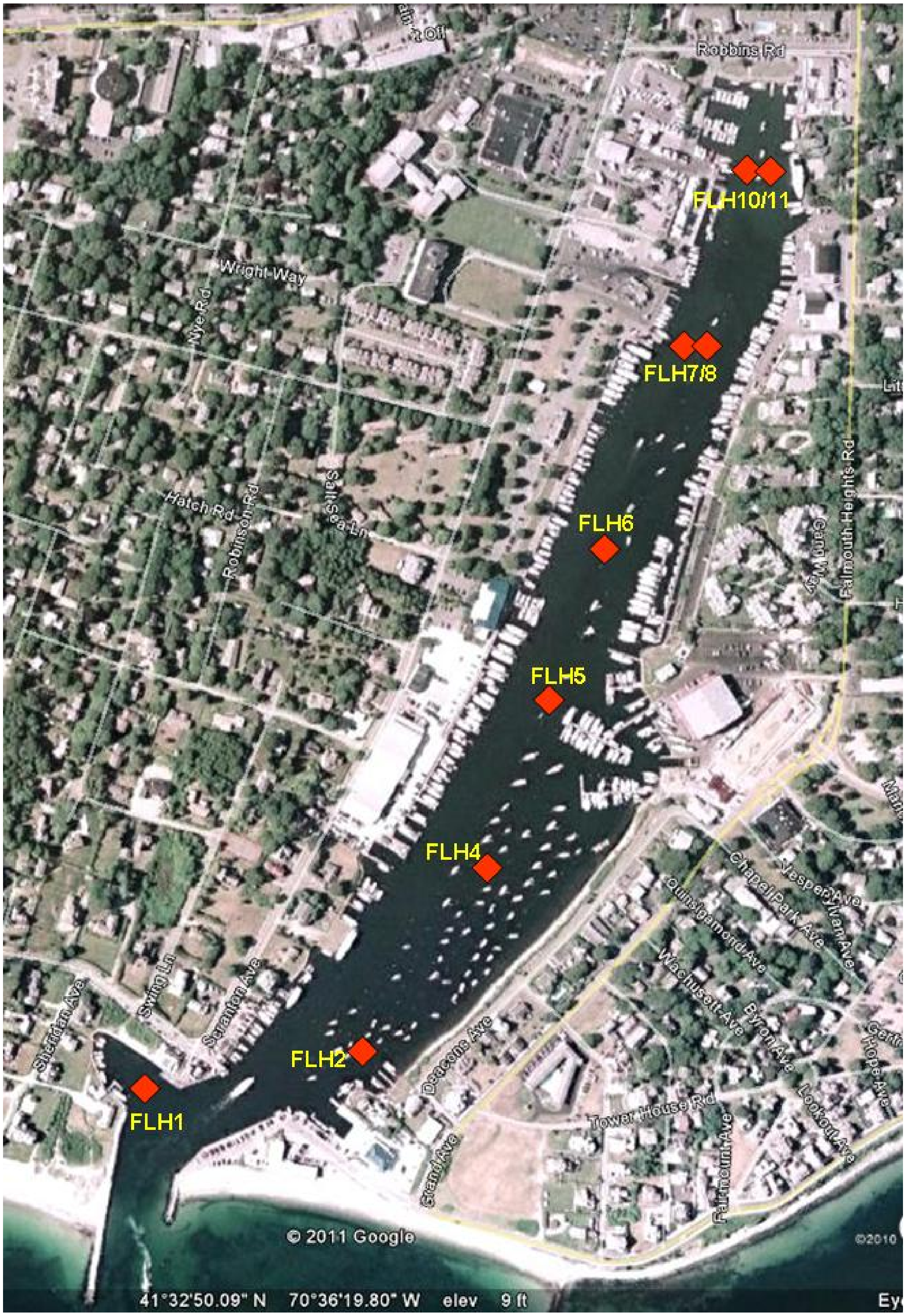

Figure VII-7. Aerial photograph of the Falmouth Inner Harbor system showing location of benthic infaunal sampling stations (red symbols).

Falmouth Inner Harbor Infaunal Characteristics:

Overall, the infauna survey indicated that the outer and inner portions of Falmouth Inner Harbor are presently supporting moderately to significantly impaired benthic infaunal habitat, associated with organic matter enrichment and periodic oxygen depletion (Table VII-3). It appears that organic deposition in these areas is the cause of the stress, consistent with the bottom water oxygen levels and phytoplankton biomass (Table VII-1 and VII-2). There also appears to be possible disturbance effects in the outer basin that are occurring in concert with nutrient related stresses. These disturbance effects are likely due to harbor or dredging activities. Animal communities colonizing sediments within both the outer and inner basins are moderately diverse (15 and 19 species, respectively) and productive (>400 individuals per sample). Both basins ranked similarly based upon the key community indices, the Weiner Diversity Index (H') with values of 2.6 and 2.7, respectively and Evenness with values of 0.67 and 0.65, respectively. Based only upon the number of species and individuals and the community diversity and Evenness metrics, these communities would be classified as moderately impaired. When the species dominating the communities are considered, this assessment is supported with the modification of a higher level of impairment in the outer basin. While the inner basin benthic animal communities are dominated by species indicative of an moderate level of organic matter enrichment (amphipods, spionids) the outer basin supported high numbers of organic enrichment indicators (tubificids, capitellids) comprising ~50% of the population. The community divide being approximately at the high density marina area, below water quality station FIH-2 - benthic station FLH-5 (see Section VI, Figure VII-7). This pattern of organic enrichment and habitat quality is consistent with the generally high chlorophyll levels and oxygen depletion observed throughout the Harbor system. However, the unconsolidated nature of the sediments at some sites within the outer basin suggest that disturbance of the surficial sediments by boat traffic at some sites may also be an additive factor, not seen in the inner basin. This observation was taken into account for guiding restoration of benthic animal habitat within the Falmouth Inner, and in placing the sentinel station well within the inner basin where sediments were consolidated and sediment disturbance was not observed at any of the survey sites.

Table VII-3. Benthic infaunal community data for the Falmouth Inner Harbor Embayment System. Estimates of the number of species adjusted to the number of individuals and diversity (H’) and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m2). Stations refer to map in Figure VII-7.

	Station	Total Species	Total Individuals	# Species Calc @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Falmouth Inner Harbor Embayment System						
Lower Basin	1,2,4,5,6	15	482	10	2.57	0.67
Upper Basin	7,8,10,11	19	931	12	2.71	0.65
Station numbers refer to ID's on map presented.						

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

Classification of habitat quality necessarily included the structure of the estuarine basin, specifically that it is fully representative of a tidal embayment, as opposed to a tidal river or salt marsh basin. Integration of all of the metrics clearly indicates that the inner and outer basins of the Falmouth Inner Harbor System are generally supporting benthic animal habitat that is moderately to significantly impaired. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the upper reach of the Harbor presently range from 0.58 - 0.52 mg TN L^{-1}, a level generally found associated with a low to moderate level of impairment of benthic animal habitat in southeastern Massachusetts estuaries.

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-8). As is the case with some systems on Cape Cod, the enclosed waters of Falmouth Inner 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 high density of moored boats and active marina basins. The conditional closure may also be due in part to bacterial concerns related to runoff from impermeable surfaces into the harbor waters, as well as natural fauna (though this is likely a minor factor in this system). Despite the status of conditionally approved for the main harbor basins, the Falmouth Inner Harbor system has also been classified as supportive of specific shellfish communities (Figure VII-9). The major shellfish species with potential habitat within the Falmouth Inner Harbor Estuary is quahogs (*Mercenaria*). A small portion of the harbor along the uppermost reach of the inner basin has been identified as potential habitat supportive of soft shell clams (*Mya*). It should be noted that the observed pattern of shellfish growing area is consistent with the observed organic rich sediments within the inner harbor. The MassDMF assessment is also in line with the present MEP assessment given the lack of shellfish habitat in the lower basin with its soft unconsolidated organic enriched sediments. Improving benthic animal habitat quality within the basins of Falmouth Inner Harbor should also expand the shellfish growing area within this system. This will not necessarily result in the opening of shellfishing beds as the underlying concern over potential sources of bacterial contamination will still exist.

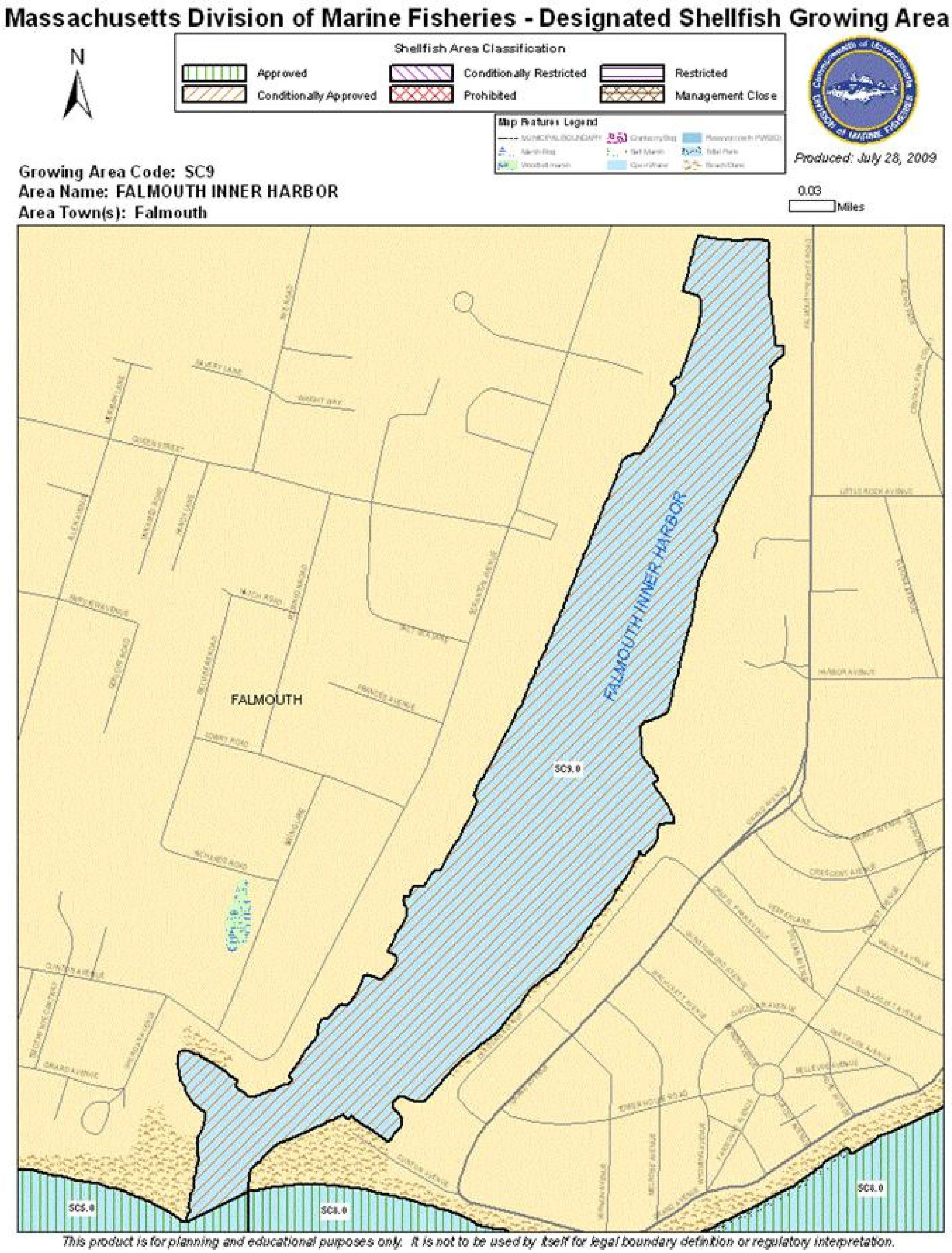

Figure VII-8. Location of shellfish growing areas in the Falmouth Inner Harbor embayment system and the status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

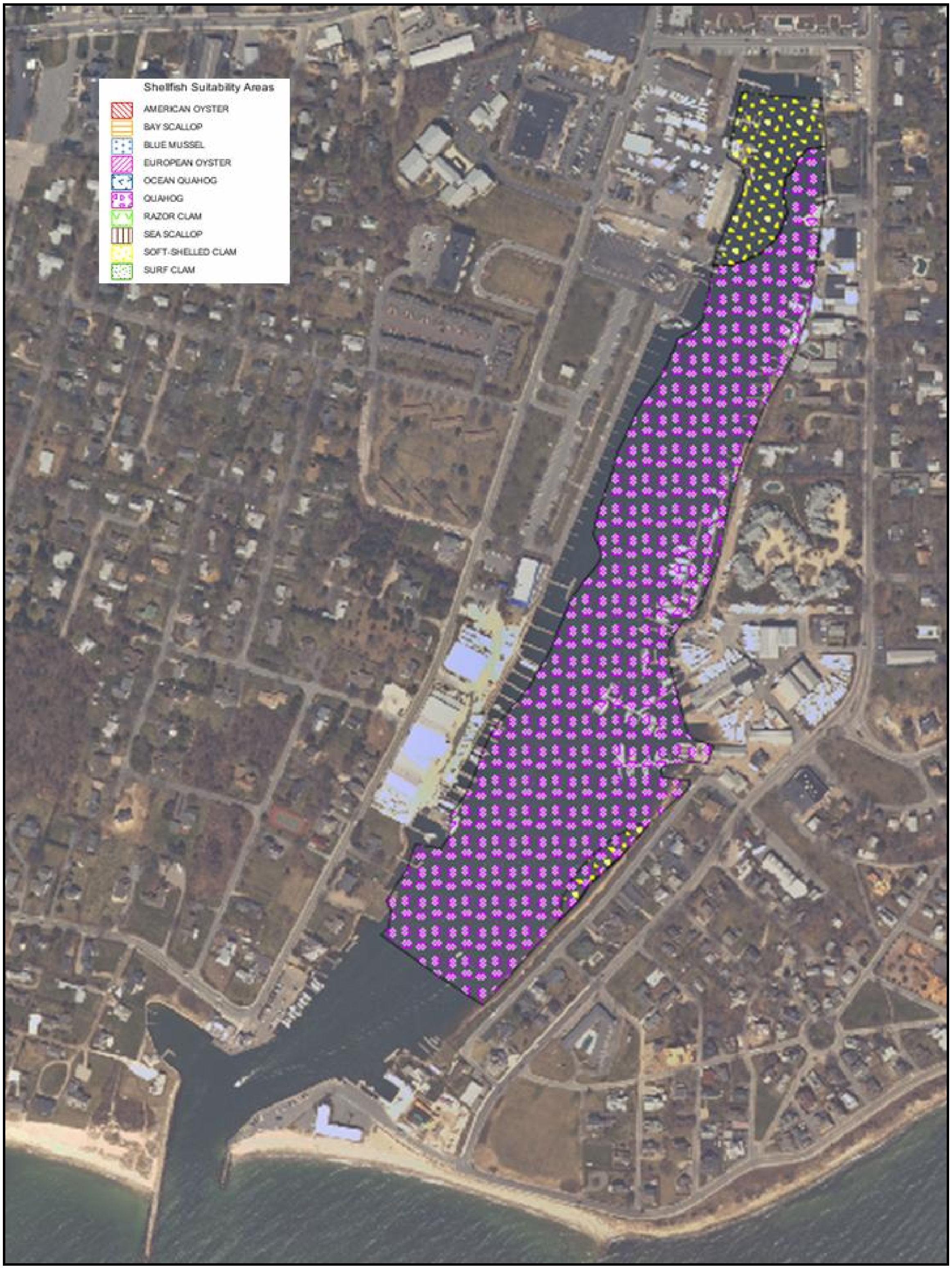

Figure VII-9 Location of shellfish suitability areas within the Falmouth Inner Harbor Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

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 to support threshold development for the Falmouth Inner Harbor Embayment System by the MEP and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline Water Quality Monitoring Program conducted by staff and graduate researchers at and with analytical support from the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

The Falmouth Inner Harbor System is an artificial open water embayment significantly altered by human activity over the past approximately 100 years. The estuary was created by opening a "fixed" inlet between a coastal freshwater pond and Vineyard Sound. Continuing human activity further transformed the estuarine basin into an active harbor with a shoreline armored and bulkheaded, with very little shoreline open for the development of fringing salt marsh. Regardless of its formation, this estuary is now functioning as an open water tidal embayment to Vineyard Sound and must be managed as such. However, based on the history of both this system, it likely has not supported any significant eelgrass beds over the past 60 years.

Falmouth Inner Harbor is presently a simple estuarine system, with a single tidal inlet to a single long narrow basin. The present inlet is armored and leads into a main basin that supports multiple marinas and significant vessel activities. Management of ecological changes and impairments of within this semi-enclosed system must be considered not only relative to nutrient enrichment from an increasingly developed coastal watershed but also the structural changes that have occurred over the during the last century and its role as an active harbor system today. In addition, each of 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. Falmouth Inner Harbor has not supported eelgrass over the past half century and likely has not supported eelgrass beds since its creation. The key underlying cause of the absence of historic eelgrass coverage in this system stems from the fact that it is an artificial embayment significantly altered by human activity over the past approximately 100 years. As eelgrass beds could not be documented to exist, either historically or presently, the thresholds analysis for this system is necessarily focused on restoration of their impaired infaunal animal habitats resulting in part from oxygen depletion and organic matter enrichment. However, it is likely that nitrogen management will improve eelgrass and infaunal habitat within down-gradient near shore waters of Vineyard Sound. At present, the Falmouth Inner Harbor Estuary is beyond its ability to assimilate nitrogen without impairment and is showing a moderate level of nitrogen enrichment, with moderate to significant impairment of 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.

Table VIII-1. Summary of nutrient related habitat quality within the Falmouth Inner Harbor Embayment System in the Town of Falmouth, MA, based upon assessments detailed in Section VII. The Upper and Lower Basins are approximately the landward upper ~1/2 of the Harbor and seaward lower ~1/2 of the Harbor, respectively.

Health Indicator	Falmouth Inner Harbor Embayment System	
	Outer Basin	**Inner Basin**
Dissolved Oxygen	MI[1]	MI/SI[2]
Chlorophyll	MI/SI[3]	MI[4]
Macroalgae	H[5]	H[6]
Eelgrass	--[7]	--[8]
Infaunal Animals	H/MI[9, 10]	MI[9, 11]
Overall:	**MI/SI[12]**	**MI/SI[13]**

1- mooring oxygen <5mg/L 8%, <4mg/L 1% of time, generally 5-8 mg/L, daily excursion ~2.5 mg/L WQMP: <5 mg/L 22%, <4 mg/L 2%, 27 sampling dates
2- mooring oxygen <6mg/L 60%, <5mg/L 28% of time, periodically to <4mg/L (3%), daily excursion ~3 mg/L. WQMP: <5 mg/L 44%, <4 mg/L 11%, periodically < 3 mg/L,, 27 sampling dates
3- levels moderate/high, mooring average 13.5 ug L^{-1}, >10ug L^{-1} 65% of record; blooms >20-25 ug L^{-1}; WQMP: high chlorophyll-*a*, long term average 14-19 ug L^{-1}, 27 sampling dates
4- levels moderate/high, mooring average 12.4 ug L^{-1}, >10ug L^{-1} 57% of record; blooms >20-25 ug L^{-1}; WQMP: high chlorophyll-*a*, long term average 19-21 ug L^{-1}, 27 sampling dates
5- drift algae generally absent, some small patches of sparse Gracillaria; Sediments: soft organic enriched muds, generally oxidized surface..
6- drift algae not observed; Sediments organic rich muds, generally oxidized surface.
7- artificial open water basin, no historical evidence of eelgrass beds, but possibly some periodic patches
8- artificial open water basin, no historical evidence of eelgrass beds
9- high numbers of individuals, moderate species (15-19), diversity (~2.6) and Evenness (~0.66).
10- stress indicator organic enrichment indicator species (capitellids, tubificids) account for ~50% of population with few mollusks or deep burrowers
11- some stress indicator species but generally dominated by intermediate organic enrichment species, amphipods (Ampelisca, spionids) with few mollusks or deep burrowers
12- Moderately to Significantly impaired benthic animal habitat, present community indicative of moderate to significant impairment, but oxygen depletion (rarely <4 mg/L) and high phytoplankton biomass (14-19 ug L^{-1}) indicate a moderate to high level of impairment. Dominant species indicative of unstable organic enriched system, stress indicators are ~50% of population (capitellids and tubifids), may be disturbance enhancement of nitrogen related stresses in lower region of basin..
13- Moderately impaired benthic animal habitat, present community indicative of moderate impairment, but oxygen depletion (periodically <3 mg/L) and high phytoplankton biomass (20 ug L^{-1}) indicate a moderate/significantly level of impairment. High organism numbers also indicative of unstable system, stress indicators (same as outer basin) are ~10%-25% of population, patches of dense amphipod mats mid Harbor.

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

Key water quality parameters, oxygen and chlorophyll, supported the contention that inner and outer basins of Falmouth Inner Harbor are impaired by nitrogen enrichment. Both continuous records of oxygen and multi-year periodic monitoring samples indicate that the inner and outer basins of the Harbor show moderate to significant levels of oxygen depletion consistent with the nitrogen enriched conditions of harbor waters. Oxygen conditions within the inner basin also exhibited large daily excursions in oxygen levels (~3 mg L^{-1}) ranging from oxygen concentrations over 8 mg L^{-1} (air equilibration) to hypoxic conditions where levels declined to <4 mg L^{-1}. Oxygen measurements by the water quality monitoring program found oxygen depletion to <3 mg $L^{-1}$and to <4 mg L^{-1} on 10% of the sampling dates. 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 several large algal blooms that were observed during the meter deployment period as well as the high rates of photosynthesis (carbon fixation) and the rapid declines in oxygen after sunset stemming from respiration.

Multiple intense phytoplankton blooms were observed by the MEP in the inner basin, where chlorophyll-*a* regularly increased to 15-20 ug L^{-1} and a few periods of bloom activity where chlorophyll-*a* concentrations were between 20 and 25 ug L^{-1}. The periodic low levels of oxygen observed in this system is indicative of moderate habitat impairment, consistent with the elevated chlorophyll-*a* levels, and also indicative of nitrogen enrichment (mooring chlorophyll-*a* average 12.4 ug L^{-1}; monitoring program averages 19-21 ug L^{-1}) . In the uppermost reaches of the Falmouth Inner Harbor system, chlorophyll-*a* exceeded the 10 ug L^{-1} benchmark 57 percent of the time. Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

The levels of oxygen observed in the outer basin is indicative of a moderate to significant impairment of benthic animal habitat stemming from nitrogen enrichment, consistent with the high chlorophyll-*a* levels. For comparison, periodic oxygen depletions to <4 mg L-1 are generally associated with stress to benthic animals and average chlorophyll levels >10 ug L^{-1} have been used to indicate eutrophic conditions in embayments.

Similar to the inner basin, the outer basin of the Falmouth Inner Harbor System also exhibits evidence of nitrogen-related habitat impairment, as seen in both periodic oxygen depletions and high phytoplankton biomass. While oxygen concentrations generally ranged between 5 and 8 mg L^{-1} levels periodically dropped below 5 mg L^{-1} and sometimes to <4 mg L^{-1}. Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. These moderate levels of oxygen depletion, are somewhat less than might be expected from the level of organic enrichment indicated by the high measured chlorophyll levels. Chlorophyll levels from the continuously recording sensors were generally between 10 and 20 ug L^{-1} and peaked at 35 ug L^{-1}, averaging 13.5 ug L^{-1}. Similarly, the water quality monitoring program found average levels at the mid Harbor and lower Harbor stations (FIH 2 & 3) of 19 and 14 ug L^{-1}, respectively, again well above the 10 ug L^{-1} benchmark

The levels of oxygen observed in the outer basin is indicative of a moderate impairment of benthic animal habitat stemming from nitrogen enrichment, consistent with the high chlorophyll-*a* levels. For comparison, periodic oxygen depletions to <4 mg L-1 are generally associated with stress to benthic animals and average chlorophyll levels >10 ug L^{-1} have been used to indicate eutrophic conditions in embayments.

The levels of oxygen depletion and phytoplankton biomass within the inner and outer basins are consistent with the organic enriched sediments. The extent of dissolved oxygen depletion indicates that the upper basin of the Falmouth Inner Harbor system is presently experiencing a level of oxygen stress consistent with the high chlorophyll levels bordering on eutrophic conditions. The lower basin shows a similar pattern of oxygen depletion and elevated chlorophyll-*a*, but indicative of less nitrogen enriched conditions. This is likely the result of a greater influence of tidal exchange with the high quality waters of Vineyard Sound, compared to the upper basin. While the lower basin also had significant oxygen depletion the extent and duration were less than the upper station. However, there was little difference between chlorophyll-*a* between the basins. It is clear from the oxygen and chlorophyll-*a* measurements that most of Falmouth Inner Harbor is nitrogen enriched and beyond its ability to assimilate additional nitrogen without impairment.

Overall, the infauna survey was consistent with the levels of oxygen depletion, phytoplankton biomass, and sediment enrichment, supporting the assessment that the outer and inner portions of Falmouth Inner Harbor are presently supporting moderately to significantly impaired benthic infaunal habitat. It appears that organic deposition in these areas is the cause of the stress. There also appears to be possible disturbance effects in concert with nutrient related stresses in the outer basin, likely due to harbor or dredging activities. Animal communities colonizing sediments within both the outer and inner basins are moderately diverse (15 and 19 species, respectively) and productive (>400 individuals per sample). Both basins ranked similarly based upon the key community indices, the Weiner Diversity Index (H') with values of 2.6 and 2.7, respectively and Evenness with values of 0.67 and 0.65, respectively. Based only upon the number of species and individuals and the community diversity and Evenness metrics, these communities would be classified as moderately impaired. When the species dominating the communities are considered, it appears that there is additional impairment in the outer basin. The inner basin benthic animal communities are dominated by species indicative of a moderate level of organic matter enrichment (amphipods, spionids). While organic enrichment indicators (tubificids, capitellids) were found in both basins, these stress indicators comprised ~50% of the population of the outer basin and generally 10%-25% of the inner basin. The community divide appears to be approximately in the region of the high density marina area, below water quality station FIH-2 / benthic station FLH-5 (see Section VI; Figure VII-7). This pattern of organic enrichment and habitat quality is consistent with the generally high chlorophyll levels and oxygen depletion throughout the Harbor system. However, the unconsolidated nature of the sediments at some sites within the outer basin suggest that disturbance of the surficial sediments by boat traffic at some sites may be an additive stressor, not seen in the inner basin. This observation was taken into account in placing the sentinel station (Section VIII.2), for guiding restoration of benthic animal habitat, well within the inner basin where sediments were consolidated and sediment disturbance was not observed at any of the survey sites.

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

Obversely, Fiddlers Cove and the upper terminal basins of Rands Harbor along Falmouth's Buzzards Bay shore are presently supporting benthic animal habitat that are generally moderately impaired. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. The animal communities colonizing sediments within the Fiddlers Cove upper basin (Canal) are moderately diverse (19 species and moderately productive (~300 individuals per sample), with index values of 2.8 (H') and 0.67 (E). It appears that organic deposition in these areas is the cause of the stress, consistent with the bottomwater oxygen levels and phytoplankton biomass. Rands Harbor is similar to Falmouth Inner Harbor having similar metrics and benthic species indicative of organic enrichment (tubificids, spionids, capitellids), with some patches of transitional species (amphipods). Fiddlers Cove and Rands Harbor also have similar levels of nitrogen enrichment associated with their waters,

Classification of habitat quality necessarily included the structure of the estuarine basin specifically that it is fully representative of a tidal embayment, as opposed to a tidal river or salt marsh basin. Integration of all of the metrics clearly indicates that the inner and outer basins of the Falmouth Inner Harbor System are generally supporting benthic animal habitat that is moderately to significantly impaired. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels (tidally averaged) within the upper reach of the Harbor presently range from 0.58 - 0.52 mg TN L^{-1}, a level generally found in associated analogous embayments: Fiddlers Cove and Rands Harbor, which average 0.56 mg TN L^{-1} and 0.57 mg TN L^{-1}, respectively, and other southeastern Massachusetts estuaries showing impairment of their benthic animal habitats.

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 Falmouth Inner Harbor Embayment System is based primarily upon the nutrient and oxygen levels and current benthic community indicators, as there is no history of eelgrass colonization of these basins. 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 Falmouth Inner Harbor Embayment System presently shows a moderate to significant impairment of its benthic animal habitat and is beyond its nitrogen threshold (i.e.,. the level of nitrogen a system can tolerate without impairment). The indications of impairment to infaunal animal habitat, as supported by the observed levels of oxygen depletion and clearly enhanced chlorophyll-*a* levels throughout its tidal reach, are similar to other estuaries with similar levels of nitrogen enrichment.

A Sentinel Station was established for the Falmouth Inner Harbor estuary for development of a nitrogen threshold target that when met will restore benthic animal habitat throughout its tidal reach. Since nitrogen levels are highest in the upper reach, the Sentinel Station for Falmouth Inner Harbor was placed within the inner basin and was established as the average of the long-term monitoring stations that were placed at the upper (FIH-1) and lower (FIH-2) margin of the inner basin. The tidally averaged total nitrogen levels within the upper reach of the Harbor are presently 0.58 mg TN L-1 (FIH-1) and 0.52 mg TN L^{-1} (FIH-2). These TN levels are comparable to other estuarine basins throughout the region that show similar levels of oxygen depletion, organic enrichment and moderately impaired benthic animal habitat. Given that in numerous estuaries it has been previously determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat (e.g., Eel Pond, Parkers River, upper Bass River, upper Great Pond, upper Three Bays, as well as the 7 inner basins of Pleasant Bay), this level is deemed most appropriate for restoration of the basins comprising Falmouth Inner Harbor. It should be noted that estuaries with TN levels >0.50 mg L^{-1} (like Rands Harbor and Fiddlers Cove in Falmouth) show benthic animal impairments similar to the present condition of Falmouth Inner Harbor. Watershed management to meet the restoration threshold for benthic animal habitat is the focus of the nitrogen management threshold analysis (Section VIII.3).

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen threshold developed in the previous section was used to determine the reduction of total nitrogen mass required for restoration of infaunal habitats in the Falmouth Inner 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 (a location mid-way between FIH-1 and FIH2) chosen for Falmouth Inner Harbor. It is important to note that load reductions can be produced by reduction of any or all sources of nitrogen. 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 31% 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.

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. For example, removal of 34% of the septic load from the Upper Harbor watershed results in a 27% reduction in total watershed nitrogen load within the Upper Harbor Watershed. 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 24% are required in the system.

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

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

sub-embayment	Present septic load (kg/day)	Threshold septic load (kg/day)	Threshold septic load % change
Upper Harbor	2.015	1.330	-34.0%
Lower Harbor	3.023	1.995	-34.0%
Morse Culvert	0.477	0.477	-0.0%
System Total	5.515	3.802	-31.1%

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 Falmouth Inner Harbor System. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Upper Harbor	2.573	1.888	-26.6%
Lower Harbor	3.860	2.832	-26.6%
Morse Culvert	0.764	0.764	-0.0%
System Total	7.197	5.484	-23.8%

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Harbor	1.888	0.219	0.629
Lower Harbor	2.832	0.219	0.632
Morse Culvert	0.764	-	-
System Total	5.484	0.438	1.261

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the Falmouth Inner Harbor System. The threshold is 0.50 mg/L for a station (black dot) located midway between water quality stations FIH-1 and FIH-2.				
Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Upper Harbor	FIH-1	0.5848	0.5240	-10.4%
Upper Harbor*	Sentinel	0.5541	0.5001	-9.7%
Lower Harbor	FIH-2	0.5233	0.4761	-9.0%
Lower Harbor	FIH-3	0.4677	0.4511	-3.5%
* The sentinel threshold station was derived by taking the average of stations FIH-1 and FIH-2				

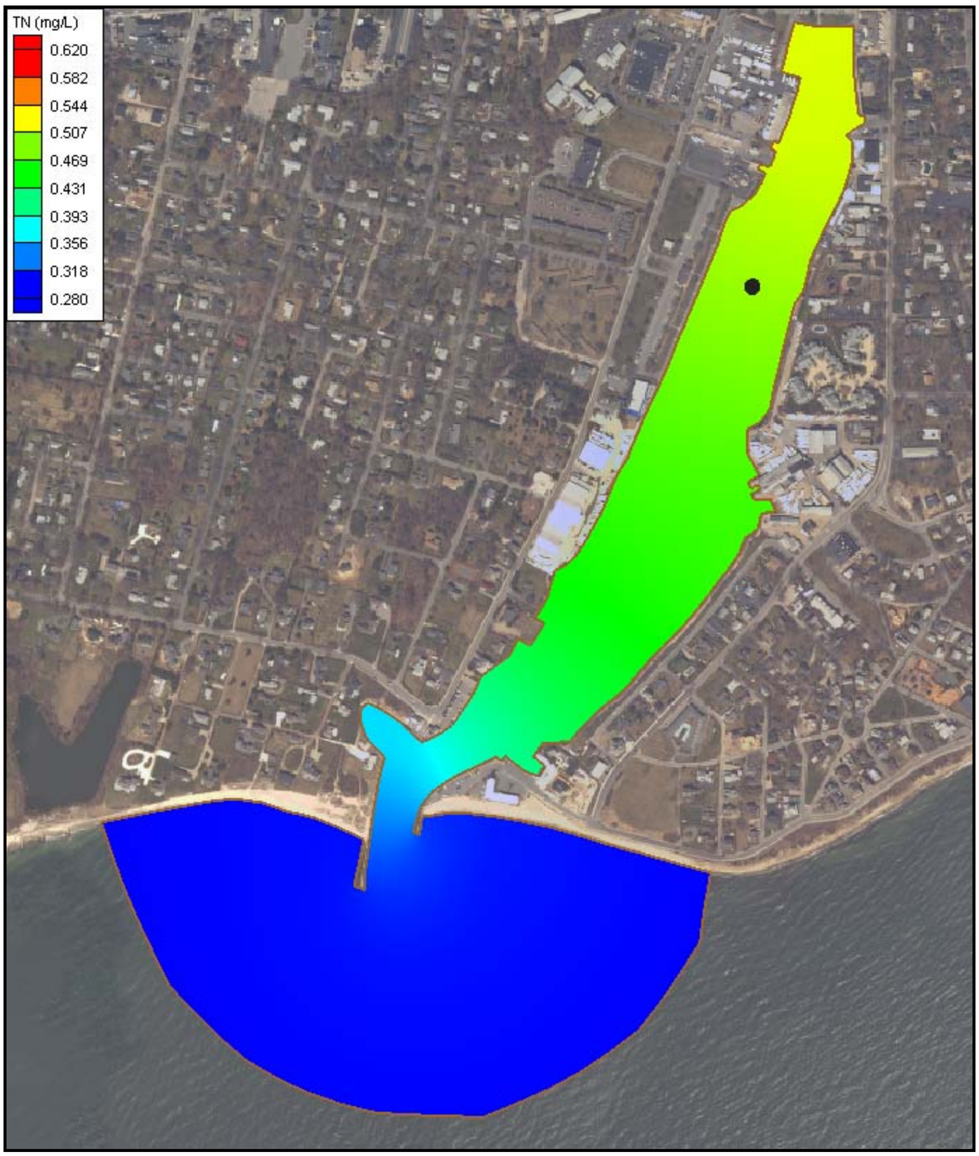

Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Falmouth Inner Harbor estuary, for threshold conditions. Threshold station is shown (concentration of 0.50 mg TN/L at the black symbol)

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