Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Megansett - Squeteague Harbor Estuarine System Towns of Falmouth and Bourne, Massachusetts

University of Massachusetts Dartmouth
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Massachusetts Department of
Environmental Protection

FINAL REPORT – December 2015

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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 Megansett Harbor and Squeteague Harbor embayment system, two coastal embayments within the Town of Falmouth and Bourne, Massachusetts. Analysis of the linked Megansett Harbor and Squeteague 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. Completion of this analysis also advances the Town of Bourne's understanding of the needs for nitrogen management in its coastal systems. As part of the MEP approach, habitat assessment was conducted on the embayments 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 and Bourne 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 Megansett-Squeteague Harbor embayment, (2) identification of all nitrogen sources (and their respective N loads) to the waters of the embayment, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within the waters of the embayment, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in the embayment, 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 Towns) for the respective protection and restoration of the Megansett Harbor and Squeteague 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 linked Megansett Harbor and Squeteague Harbor embayment system split between the Town of Falmouth and Bourne are 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 and Bourne have recognized the severity of the problem of eutrophication and the need for watershed nutrient management and Falmouth is currently developing a Comprehensive Wastewater Management Plan which the Town plans to implement upon its completion. The Town of Falmouth has been working steadily towards completing MEP analyses and implementing wastewater planning in other nearby regions not associated with the Megansett-Squeteague Harbor system, specifically the Fiddlers Cove and Rands Harbor embayment systems as well as other estuaries of the town (specifically, Quissett Harbor, Wild Harbor, West Falmouth Harbor, Little Pond, Falmouth Inner Harbor, Oyster Pond, Great Pond, Green Pond, Bournes Pond, Eel Pond/Childs River and Waquoit Bay) in order to give the Town of Falmouth the necessary results to plan out and implement a unified town-wide approach to nutrient management. This has also been occurring in the Town of Bourne, albeit in a much more sporadic and incremental manner as the Town of Bourne's engagement with the MEP has been limited. The MEP assessment of the Megansett-Squeteague system is the last of 14 MEP assessment for the Town of Falmouth and the third of five embayment assessments for the Town of Bourne. 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 an 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 an 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 by the Buzzards Bay Project, in the CCC models, and other relevant models. However, the Linked Model differs from other nitrogen management models in that it:

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

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

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 hydraulically connected Megansett Harbor and Squeteague Harbor embayment system by using site-specific data collected by the MEP and water quality data from the Falmouth PondWatch Program (see Section 2) as well as the Coalition for Buzzards Bay (CBB) BayWatchers Program (assisted technically until 2008 by the University of Massachusetts-SMAST Coastal Systems Program). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Falmouth and Bourne Planning Departments, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Megansett-Squeteague Harbor embayment system and the sub-embayments of each system as appropriate (current and build-out loads are summarized in Table IV-3). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Megansett-Squeteague Harbor embayment system. Once the hydrodynamic properties of the estuarine systems were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates specific to the embayment. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Buzzards Bay source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Megansett-Squeteague Harbor system were used to calibrate the water quality models, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic models were 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. High habitat quality was defined as supportive of eelgrass and infaunal communities. Dissolved oxygen and total pigment (mainly 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 protection/restoration of eelgrass and infaunal habitats in the Megansett Harbor and Squeteague Harbor embayment system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for the overall 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 each community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for protection/restoration of this slightly 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 Megansett-Squeteague Harbor embayment system split between the Towns of Falmouth and Bourne. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to each of the embayments. 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 59% - 79% of the controllable watershed load to Squeteague Harbor and Megansett Harbor respectively and are more manageable than other 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 both the Megansett Harbor and Squeteague Harbor embayment system, based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure. It is important to note that all of the basins within this estuarine system have been altered, generally in ways that effect circulation of tidal exchange. Megansett Harbor was originally more open than it is today, with the large island of Scraggy Neck disconnected with flow between the island and mainland. To provide better access to the island, a causeway was constructed to support a roadway. The causeway redirected flows around the new “neck or peninsula” altering the circulation within Megansett Basin. The present inlet to Squeteague Harbor is partially armored and leads into a well defined channel that is connected to the main basin that serves as a small and shallow mooring area for recreational boats and residential docks. Fiddlers Cove, which discharges to Megansett Harbor was a small salt marsh dominated basin and tidal creek that was modified and dredged to create a protected harbor and canal for boats. Although there have been numerous alterations to the various tributary basins within the Megansett/Squeteague Estuary, the systems appears to be functioning as a complex estuary today. Regardless of their formation, this complex of estuaries is now functioning as tributary embayments to Buzzards Bay and must be managed as such. Management of ecological changes and impairments of these semi-enclosed systems 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.

At present, the Megansett-Squeteague Harbor Estuarine System is only slightly beyond its ability to assimilate nitrogen without impairment and is showing a moderate level of nitrogen enrichment, with generally moderate impairment of eelgrass and infaunal habitats (Table VIII-1). As eelgrass beds could were well documented, both historically and presently, the threshold analysis for the system is necessarily focused on restoration of both the eelgrass habitat and their slightly impaired infaunal animal habitats resulting in part from slight oxygen depletion and organic matter enrichment. Nitrogen management within these two linked systems will improve eelgrass and infaunal habitat within the down-gradient near shore waters of Buzzards Bay.

Oxygen records obtained from the moorings (6) deployed throughout the Megansett/Squeteague Harbor Estuarine System indicate moderate organic matter enrichment resulting in periodic low to moderate oxygen depletion within both Megansett Harbor and Squeteague Harbor basins. Oxygen stress was only indicated within the deepest portion of Megansett Harbor which is a natural depositional area receiving both phytoplankton deposition and macrophyte detritus (macroalgal and eelgrass). This basin may also be influenced by discharging high nutrient waters from Fiddlers Cove and Rands Harbor whose tidal inlets are only close to the margin of the deep basin.

Oxygen in the nearshore adjacent eelgrass beds in the north cove region (basin adjacent Eustis Beach) had only moderate daily excursions. The low organic enrichment of the system is also demonstrated by the general lack of algal blooms with the exception of 1 bloom observed during the later part of the mooring deployment period (first week of September). Similarly, oxygen at the margin of the outer basin in the more open water area of Megansett Harbor, compared to the two other Megansett Harbor moorings, also showed only relatively low daily excursions in oxygen levels. These moderate oxygen levels are primarily the result of respiration by low to moderate phytoplankton biomass and relatively quiescent waters. The oxygen levels and excursions were typical of relatively low organic enrichment, consistent with the general lack of algal blooms. The low frequency of oxygen depletion observed in this system is indicative of high quality habitat, which is also consistent with the generally low total pigment levels, also indicative of low nitrogen enrichment in this portion of Megansett Harbor. In contrast, in the deepest waters of the main basin of Megansett Harbor, low to moderate daily excursions in oxygen levels were observed. It appears likely that some of the oxygen depletion at this site is due to the structure of the basin, where organic matter deposition occurs in the deep water off shore of the eelgrass beds in the shallows and as a result of outflows from Fiddlers Cove and Rands Harbor. The low oxygen does not appear to be related to nitrogen or total pigment levels but rather because the "hole" is acting as a "particle trap" similar to the 3 deep basins in Nantucket Harbor. Accumulation of macrophyte detritus in this area of Megansett basin was confirmed by diver observations (S. Aubrey personal communication). The lower oxygen levels compared to the other two mooring locations in Megansett Harbor are inconsistent with the generally low total pigment levels in this portion of Megansett Harbor. It appears that like Nantucket Harbor, the deep basin of Megansett Harbor has periodic oxygen depletion related to its structure as a natural depositional area, rather than local processes related to eutrophication.

The enclosed shallow basin of Squeteague Harbor has similar oxygen conditions as the shallower marginal areas of Megansett Harbor and tended to show less oxygen depletion than the deep basin of Megansett Harbor. Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of potential oxygen stress, but that has not been observed within Squeteague Harbor. Within the eastern section of the main basin furthest removed from the inlet connecting the Megansett Harbor basin to the Squeteague Harbor basin, only relatively small daily excursions in oxygen levels were observed. The western section of the main basin of Squeteague Harbor also had only moderate daily excursions in oxygen levels. The generally high oxygen levels of >6 mg L^{-1} during 95% of the record do not indicate stress or benthic animal habitat impairment. This is also consistent with the total nitrogen levels in the Squeteague Harbor portion of the system (0.45 mg L^{-1}, tidally averaged) and observed total pigment levels that are consistent with moderate nitrogen enrichment of Squeteague Harbor (average total pigment, 11.2 ug L^{-1}).

Overall conditions within the Squeteague Harbor basins include generally high oxygen levels, with only moderate total pigment level (~11 ug L^{-1}), stemming from the moderate nitrogen enrichment (TN <0.50 mg L^{-1}). These conditions are generally associated with low stress to benthic animal communities.

The observed water column metrics (oxygen, total pigment as chlorophyll-a + pheophytin, total nitrogen) are consistent with the infaunal communities within the Megansett/Squeteague estuarine basin. The infauna surveys indicated that the Megansett/Squeteague Estuarine System is currently supporting highly productive and diverse benthic communities throughout its component tidal basins. However, there is a modest gradient in benthic community metrics with highest quality habitat in the Megansett Harbor basin closest to the high quality waters of Buzzards Bay to the moderate to high quality habitat in the northern region of Squeteague Harbor, furthest from Buzzards Bay and with the lowest flushing rate.

Both the northern cove and the southern region bordering the deep basin of Megansett Harbor are supporting eelgrass beds which are relatively stable, but showing a gradual decline from 1995-2012. Not surprising these areas are also supporting high quality benthic animal habitat with high numbers of species and moderate numbers of individuals with high diversity and evenness. Equally important is the very low numbers of stress and organic indicator species (tubificids and capitellids) and numbers of molluscs and crustaceans. Similarly, the channel between Megansett Harbor and the main basin of Squeteague Harbor also shows high quality benthic animal habitat with metrics approaching the outer basin. The channel supports a diverse infaunal community with high Evenness and moderate to high numbers of species and individuals, however, stress indicator species, mainly tubificids, were present and represented as much as 20% of the community. While the community was found to be representative of high quality habitat, the presence of these stress indicators should be tracked. It should be noted that it is possible that disturbance due to the high velocity flows in the channel and boating activities may be partly the reason for the presence of stress indicator species along with enhanced deposition stemming from the drop in velocity as the channel widens at either end. This localized disturbance effect is supported by the observation that these stress indicators were sparse in the innermost basin of Squeteague Harbor. Squeteague Harbor also showed moderate to high quality benthic animal habitat with moderate to high numbers of species, diversity and high numbers of individual and Evenness. There is some indication of moderate organic enrichment as amphipods dominate some areas which suggests that this basin may be nearing its ability to assimilate additional nitrogen without impairment. The spatial pattern of benthic habitat quality is similar to other estuaries on Buzzards Bay with similar water quality and specific nitrogen loading.

While infauna habitat is generally of high quality throughout the main basins of the Megansett/Squeteague Harbor Estuary, all of the available information on eelgrass within this Estuarine System indicates that although the outer basin of Megansett Harbor continues to support significant eelgrass beds, there is some evidence of a decline in acreage. The decline is in both the southern and northern major eelgrass beds (Section VII.2) and is clearly seen in surveys since 1995 where field verification was performed. The absence of significant eelgrass habitat within the channel and Squeteague Harbor basin indicates that benthic infauna habitat is the main resource for assessment of impairment by nitrogen enrichment and the focus of management for these basins, while eelgrass habitat should be the focus within the outer basin of Megansett Harbor.

3. Conclusions of the Analysis

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 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. 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 Megansett-Squeteague Harbor Embayment System is based primarily upon the nutrient and oxygen levels, the distribution of eelgrass and current benthic community indicators.

The Megansett/Squeteague Harbor Estuarine System presently shows a moderate level of impairment to eelgrass habitat within its Outer Basin (Megansett Harbor). The impairment is based upon the recent temporal trend in loss of eelgrass from eelgrass areas in both the northern and southern margins of the basin, particularly where the southern beds impinge upon deeper water. Both the location and the temporal trend is consistent with nitrogen enrichment. However, that the rate of loss has been gradual and relatively recent indicates that this estuary is only just beyond its nitrogen threshold (i.e. the level of nitrogen a system can tolerate without impairment). The presence of stable dense eelgrass beds throughout the shallow margins of

Megansett Harbor and the generally high quality benthic animal habitat throughout the embayment system (with only a slight indication of incipient moderate impairment in the innermost reaches of Squeteague Harbor) also indicates a system only just beyond its threshold. The relatively low levels of nitrogen are consistent with the generally high quality of eelgrass and benthic animal habitat within this system, but the clear enrichment in the areas losing eelgrass is consistent with the low level of impairment documented for this estuary.

Restoring the impairments to eelgrass and protecting benthic animal habitat is the focus of the nitrogen management threshold analysis (Section VIII.3). As eelgrass within the Megansett /Squeteague Harbor Estuary is critical habitat that structures the productivity and resource quality of the entire system, and it is presently showing moderate impairment, restoration of this resource is the primary target for overall repair of this system. Nutrient management planning for restoration of the eelgrass habitat at the boundary between the Outer and Inner Basins should focus on reducing the level of nitrogen enrichment in basin waters through watershed nitrogen management and managing tidal exchange as appropriate.

Based upon the information above and in Chapter VII and the level of eelgrass impairment observed, it appears that the system is presently only slightly beyond its nitrogen threshold for sustainable eelgrass coverage. This assessment is based upon several factors as follows: 1) the distribution of the remaining eelgrass habitat, 2) the observed loss of eelgrass in the northern and southern eelgrass beds bordering the deep basin of Megansett Harbor, 3) that the decline is slow and relatively recent and 4) that the system is only moderately nitrogen and organic matter enriched.

A major finding of the MEP clearly indicates that a single total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of the Great, Green and Bournes Pond Systems, Popponesset Bay System, and the nearby Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay, among many other systems analyzed by the MEP. This is almost certainly going to be true for the other embayments within the MEP area, as well, inclusive of Megansett-Squeteague Harbor.

The threshold nitrogen levels for the Megansett Harbor and Squeteague Harbor embayment system in Falmouth and Bourne were determined as follows:

Megansett-Squeteague Harbor Threshold Nitrogen Concentrations and Loads

- Following the MEP protocol, the restoration target for the Megansett-Squeteague Harbor system should reflect both recent pre-degradation habitat quality, take into consideration structural characteristics (historic and present) of each portion of the embayment and be reasonably achievable. Based upon the assessment data (Section VII), the Megansett-Squeteague system is presently supportive of healthy to moderately impaired habitat, depending on the component sub-basins being considered. Overall, each component of the system is only showing signs of moderate to low impairment.

- The spatial distribution of high quality and impaired habitats and associated oxygen and total pigment levels parallels the gradient in water column total nitrogen levels within this estuary. The tidally averaged total nitrogen levels were observed to be 0.33-0.36, 0.39 and 0.45-0.47 mg N L^{-1} within Megansett Harbor, the Channel and Squeteague Harbor, respectively. For Megansett Harbor a threshold for tidally averaged TN at the sentinel station (MG-2, Figure VI-1) of 0.35 mg N L^{-1} was selected to restore eelgrass habitat based upon the depth and TN levels within the stable eelgrass beds. This threshold is similar to that which was developed for West Falmouth Harbor and Phinneys Harbor, and is focused in part on restoring eelgrass where it had persisted until recently. In addition, lowering the level of nitrogen enrichment at the sentinel station will lower nitrogen levels throughout the estuary (Section VIII.3) with the parallel effect of protecting and improving infaunal habitats in the inner reaches of Squeteague Harbor. Therefore, the goal is to achieve the nitrogen target at the sentinel location and restore the historical eelgrass habitat within Megansett Harbor, resulting also in the protection and improvement of infaunal habitat throughout the 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 in Section VIII represent only one of a suite of potential reduction approaches that need to be evaluated by the community. In this present analysis, a comparison between septic loadings for present and threshold modeling scenarios was undertaken. Modeling results indicated that the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations at the sentinel station (MG-2) required approximately 20% removal of septic load (associated with direct groundwater discharge to the embayment) for the entire system.

- The 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 Section VIII, Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station (MG-2), reductions in TN concentrations of between 11% and 22% is required in the system, between the main harbor basin and the inner reaches of Squeteague Harbor. Although the above modeling results provide one manner of achieving the selected threshold level for the sentinel site within the estuarine system, the specific example does not represent the only method for achieving this goal.

It is important to note that the analysis of future nitrogen loading to the Megansett Harbor and Squeteague 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 Megansett-Squeteague Harbor estuarine system is that restoration will necessitate a reduction in the present (Falmouth 2012, Bourne 2011 and Sandwich 2010) 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 Wild 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)
Megansett Harbor	0.937	6.107	12.871	--	18.978	5.556	-22.515	2.019	0.24-0.49	0.35
Megansett Channel	0.260	0.934	2.764	--	3.699	0.386	-0.682	3.403	0.39-0.50	--
Squeteague Harbor	0.847	4.047	5.216	--	9.263	1.000	0.151	10.414	0.37-0.55	--
Combined Total	**2.044**	**11.088**	**20.852**	**0.000**	**31.940**	**6.942**	**-23.046**	**15.836**	**0.24-0.55**	**0.35[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 2000 – 2013 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 is located at the outer Megansett Harbor water quality station MG2.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Wild Harbor estuarine system in 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
Megansett Harbor	18.978	15.760	5.556	-23.545	-2.229	-17.0%
Megansett Channel	3.699	3.422	0.386	-0.669	3.140	-7.5%
Squeteague Harbor	9.263	8.741	1.000	0.146	9.888	-5.6%
Combined Total	**31.940**	**27.924**	**6.942**	**-23.545**	**10.799**	**-12.6%**

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

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I. INTRODUCTION

The Megansett Harbor and Squeteague Harbor Estuarine System is located within the Town of Falmouth and the Town of Bourne, on Cape Cod, Massachusetts. These harbors are hydraulically connected with a well defined inlet channel that exists between inner Megansett Harbor (which is the outer portion of the overall system) and Squeteague Harbor which is an enclosed tidal basin. Together these two harbors functionally constitute one ecologically connected embayment system. In addition, the overall embayment system supports two smaller tributary embayments that were previously evaluated by the MEP in 2012, Fiddlers Cove and Rands Harbor. Both these tributary embayments discharge to Megansett Harbor from the Town of Falmouth portion of the Megansett Harbor watershed. Both Megansett Harbor and Squeteague Harbor (in addition to Fiddlers and Rands) exchange tidal waters with Buzzards Bay (Figure I-1). The developed regions of the watershed to the Megansett and Squeteague Harbors estuarine system is distributed almost entirely within the Town of Falmouth and Bourne while the largely undeveloped uppermost portion of the watershed falls within the Massachusetts Military Reservation (now Joint Base Cape Cod, JBCC) that exists within the Towns of Falmouth, Sandwich and Bourne. This upper watershed within the MMR (~1/3 of watershed) is mainly undeveloped and developed areas are on sewer. This land with Town Conservation lands and water supply areas makes Public Service land which constitutes over 70% of the watershed area. As such the upper portion of the watershed within JBCC is not contributing a significant nitrogen load to the estuary. As a result, the primary stakeholders for the management and restoration of the Megansett Harbor and Squeteague Harbor System are the Towns of Falmouth and Bourne.

The Megansett Harbor and Squeteague Harbor system along with the Fiddlers Cove and Rands Harbor estuaries are some of the more intensively utilized estuarine resources in the Town of Falmouth (e.g. Fiddlers Cove supports a significant marina and Megansett Harbor has an associated Yacht Club, both having high boating effort during summer months. At a time when many other coastal ponds and bays tributary to Buzzards Bay have been severely degraded, water quality in Megansett Harbor and Squeteague Harbor, along with Fiddlers Cove and Rands Harbor, has generally remained moderately high due to the very open connection to low nutrient waters of Buzzards Bay (Megansett Harbor), the small size of the inner basins (Squeteague Harbor, Fiddlers Cove and Rands Harbor) and the large undeveloped areas of their upper watersheds. However, portions of each system (e.g. innermost portion of Squeteague Harbor, the narrow canal extending landward from the main basin of Fiddlers Cove and dredged channels of Rands Harbor) have shown indications of nutrient enrichment. Significant in maintaining the water quality within Megansett Harbor and Squeteague Harbor (as well as Fiddler and Rands) is the flushing rate and tidal exchange with the low nutrient high quality waters of Buzzards Bay.

The present open embayment structure of Megansett Harbor represents a natural, glacially defined hydrographic feature of Buzzards Bay. Squeteague Harbor is also defined by a open water basin, however, unlike Megansett Harbor it is an enclosed basin which receives tidal water from Buzzards Bay through a shallow narrow channel that has been maintained to increase access to Squeteague Harbor. Squeteague appears to have been formed as a cove by rising sea levels which was enclosed by a barrier beach formed by coastal processes to near its present morphology. Fiddlers Cove and Rands Harbor, as associated tributary sub-embayments to Megansett Harbor, also have been significantly modified historically. Fiddlers Cove and Rands Harbor specifically are artificial open water embayments significantly altered

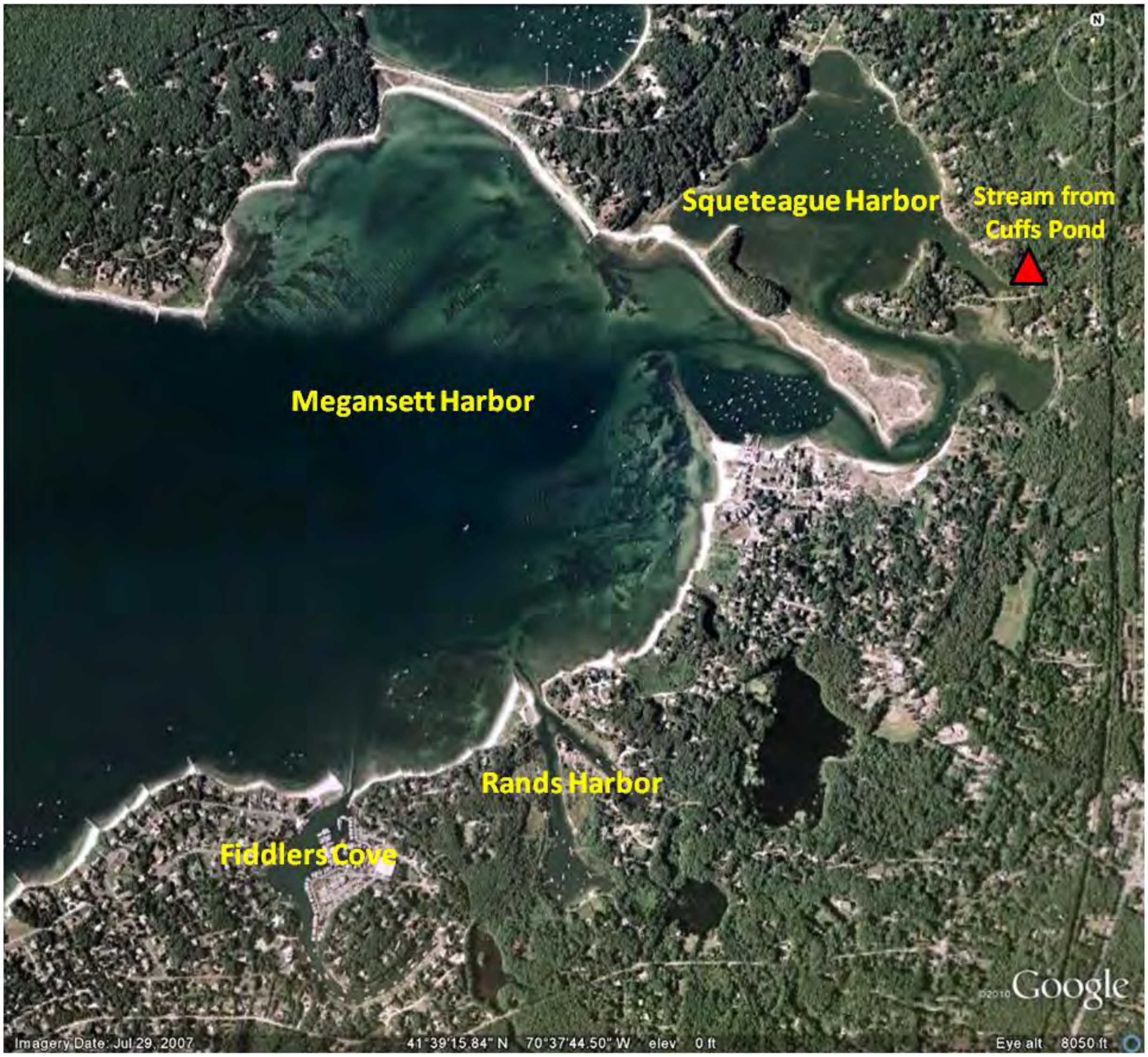


Figure I-1. The Megansett Harbor / Squeteague Harbor System study region for the Massachusetts Estuaries Project nutrient analysis. Tidal waters enter the outer Megansett Harbor from Buzzards Bay and then pass through the single inlets to Squeteague Harbor, Rands Harbor and Fiddlers Cove. A small freshwater inflow enters directly to Squeteague Harbor.

by human activity over the past approximately 100 years. Both estuaries were formed primarily as tidal salt marshes with associated tidal creeks as seen in historical maps (1880 and 1916). Human activity gradually transformed these salt marsh dominated tidal creeks into more open water systems. The tidal wetlands were removed to increase the navigability of the systems and to create protected harbors, though portions of the upper reaches of Fiddlers Cove still supported bordering saltmarsh into the 1970's. At present almost all of the tidal wetlands along the shoreline of Fiddlers Cove have been removed and replaced with hard coastal structures (e.g. riprap). Although Rands Harbor was also constructed from tidal creeks, it still maintains significant fringing salt marsh areas, particularly in the western branch. Until approximately the 1920's Rands Harbor was comprised of tidal wetland basins fed by tidal creeks connected to Buzzards Bay through a common inlet. Around the mid-1920's the salt marsh system was dredged and enlarged creating free tidal exchange and producing an open water system approximating Rands Harbor as it is structured today. Regardless of their formation, both estuaries are now functioning as tributary embayments to Buzzards Bay and must be managed as such. However, based on the history of both these systems, they likely have not supported eelgrass over the past 60 years.

Megansett Harbor and Squeteague Harbor together form a relatively complex estuarine system within which exist the Fiddlers Cove and Rands Harbor systems that taken individually are presently relatively simple estuarine systems) with Rands Harbor being the more complex of the two given that it has one inlet but two distinct branches). The larger overall Megansett Harbor / Squeteague Harbor estuary is comprised of 3 principal basins: 1) an open water basin directly connected to Buzzards Bay (outer Megansett Harbor), 2) a more enclosed basin formed behind a large jetty (inner Megansett Harbor) which feeds directly into 3) an enclosed basin (Squeteague Harbor) via a narrow shallow channel. Fiddlers Cove and Rands Harbor are two small tributary embayments to outer Megansett Harbor (Figure I-1).

All of the basins within this estuarine system have been altered, generally in ways that effect circulation of tidal exchange. Megansett Harbor was originally more open than it is today, with the large island of Scraggy Neck disconnected with flow between the island and mainland. To provide better access to the island, a causeway was constructed to support a roadway. The causeway redirected flows around the new "neck or peninsula" altering the circulation within Megansett Basin. The present inlet to Squeteague Harbor is partially armored and leads into a well defined channel that is connected to the main basin that serves as a small and shallow mooring area for recreational boats and residential docks (Figure I-2). Fiddlers Cove was a small salt marsh dominated basin and tidal creek that was modified and dredged to create a protected harbor and canal for boats. Megansett Harbor receives freshwater from groundwater discharge to the shoreline as well as a small stream that flows into Rands Harbor from the watershed. The Rands east branch stream is sourced in Cedar Lake whereas the west branch stream is sourced in Flax Pond. Similarly, Squeteague Harbor receives groundwater along its shoreline as well as surface water discharge from its upper watershed via a small stream from Cuffs Pond and hydraulically connected Long Pond. Although there have been numerous alterations to the various tributary basins within the Megansett/Squeteague Estuary, the systems appears to be functioning as a complex estuary today, Therefore, management of ecological changes and impairments of this system must be considered not only relative to nutrient enrichment from an increasingly developed coastal watershed but also in the context of the structural changes that have occurred over the last century.

Megansett Harbor, Squeteague Harbor and the associated tributary embayments of Fiddlers Cove and Rands Harbor (but more so Fiddlers Cove) are important for recreational boating. Inner Megansett Harbor supports a small yacht club and Brewer Fiddlers Cove Marina supports approximately 135 boat slips with an additional 63 indoor rack storage units. The private marina that represents a large part of the boating activity in Fiddlers Cove has two main docks, which consists of piers with floats, and slips along a seawall. The marina operates a full service boat yard and boat fueling at the marina dock is available as is electricity. Pump-out facilities for boat waste are provided by the marina.

The habitat quality of the Megansett Harbor and Squeteague Harbor system along with the associated Fiddlers Cove and Rands Harbor Systems is linked to the level of tidal flushing through the direct connection between outer Megansett Harbor and through the Squeteague Harbor inlet to inner Megansett Harbor and ultimately Buzzards Bay, which exhibits a moderate tide range of about 5 ft. Since the water elevation difference between the Bay and Harbors 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). Moreover, the degree to which the inlet / channel to Squeteague Harbor remains unobstructed is also critical to the exchange of water and the health of each component of the system. In that light, while the inlet to Squeteague harbor is only partially armored, the inlet to Fiddlers Cove is fully armored and that to Rands Harbor is partially armored, both with stone jetties. Maintenance dredging is also performed, as needed. Given the present hydrodynamic characteristics of the overall Megansett Harbor and Squeteague Harbor system, including the Fiddlers Cove and Rands Harbor embayment systems, it appears that estuarine habitat quality is mostly dependent on the level of nutrient loading to embayment waters as opposed to tidal characteristics. In Squeteague Harbor as well as Fiddlers Cove and Rands Harbor, minimal enhancements to tidal flushing may be achieved via inlet or channel modification at this time. Therefore, to maintain or enhance existing habitat quality in these systems, it will be necessary to manage nutrient inputs and transported through the respective watersheds to associated receiving waters. The details of such are a part of the MEP analysis described later in this report, specifically for Megansett Harbor and Squeteague Harbor. Nitrogen threshold conclusions have already been provided to the Town of Falmouth for Fiddlers Cove and Rands Harbor under separate cover.

Figure I-2. Squeteague Harbor (relative to outer Megansett Harbor) study region for the Massachusetts Estuaries Project nutrient analysis. Tidal waters enter the main basin of the Squeteague Harbor estuarine system from Buzzards Bay through one inlet (partially armored) connected to inner Megansett Harbor. Freshwaters enter along the embayment shoreline via direct groundwater seepage and a small freshwater stream discharging to this estuary from Cuffs Pond.

The watershed to Megansett Harbor and Squeteague Harbor is somewhat geologically complex, being composed primarily of and sand and gravel outwash from the Falmouth Moraine along the eastern shore of Megansett Harbor (including Fiddlers Cove and Rands Harbor). In contrast the upper watershed regions, particularly within JBCC (MMR) are primarily sand and gravel outwash deposits of the Mashpee Outwash Plain, which extends eastward to Nantucket Sound. These formations consist of material deposited during the retreat of the Cape Cod Lobe of the Laurentide Ice sheet. The material is highly permeable and as such, direct rainwater run-off is typically rather low for this type of coastal system and most freshwater inflow is via groundwater discharge. Originally the basins of the two Harbors were isolated from the sea, but as a result of rising sea level following the last glaciation approximately 18,000 years BP, they became estuarine systems ~6,000-8,000 years BP and colonized by salt marsh vegetation. Although these now open water embayments (specifically Squeteague Harbor, Rands Harbor and Fiddlers Cove) are converted wetland basins, they are both presently functioning as coastal embayments and need to be managed as such.

At present, Megansett Harbor does not receive direct stream discharge, with virtually all watershed input being through direct groundwater discharge. Squeteague Harbor, like Rands Harbor, however, is a tidal embayment with one small stream that is mostly fed from up-gradient ponds, firstly Cuffs Pond and secondarily Long Pond (through an intermittent connection) situated upgradient of Cuffs Pond. The small stream discharges under Megansett Road nearly adjacent to Amrita Island. The stream from Cuffs Pond is also likely to be slightly groundwater fed in addition to receiving some freshwater from up-gradient Long Pond that also serves to feed water into a cranberry bog. Inner Megansett Harbor, Squeteague Harbor, Fiddlers Cove and Rands Harbor all act as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Buzzards Bay via outer Megansett Harbor, however, the salinity characteristics of the system varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with outer Megansett Harbor. Overall, the small freshwater contributing area and large tide range result in a relatively high average salinity (>27ppt) throughout much of Megansett Harbor and Squeteague as well as Fiddlers Cove and Rands Harbor (>29 ppt and >27 ppt respectively).

Similar to other embayments on Cape Cod, Megansett Harbor and Squeteague Harbor, along with Fiddlers Cove and Rands Harbor, are mesotrophic (moderately nutrient impacted) shallow coastal estuarine systems. Neither the Fiddlers Cove or Rands Harbor systems presently or historically supported eelgrass beds, most likely because they were artificially dredged basins with moderate levels of nitrogen enrichment. However, extensive eelgrass beds presently exist immediately offshore from the inlets to both Fiddlers Cove and Rands Harbor within the shallow near shore waters of outer Megansett Harbor. The presence of eelgrass is particularly important to the use of outer Megansett Harbor as fish and shellfish habitat and in turn a source of larvae to support benthic and fish communities in Squeteague Harbor as well Fiddlers Cove and Rands Harbor. The Megansett Harbor and Squeteague Harbor system, and by association Fiddlers Cove and Rands Harbor, represents an important shellfish resource to the Town of Falmouth, primarily for quahogs and Bay Scallops. However, while shellfishing is approved year round for outer Megansett Harbor, shellfishing activities in Squeteague Harbor, Fiddlers Cove and Rands Harbor are conditionally approved (seasonally restricted) by the Massachusetts Division of Marine Fisheries. This is a result of potential bacterial contamination from watershed run-off and other possible sources such as storm run-off or marina activities as in Fiddlers Cove. Selectively open DMF segments located in the overall outer Megansett Harbor system include BB:50.3 (Squeteague Harbor, conditionally approved), BB:50.1 (Fiddlers Cove, conditionally approved) and BB:50.2 (Rands Harbor, conditionally approved). The shellfish closures and possible eelgrass loss in outer Megansett Harbor has raised public concern in recent years with regard to the health of estuarine resources within outer Megansett Harbor, Squeteague Harbor, Fiddlers Cove and Rands Harbor. The Town of Falmouth has specifically targeted nutrient management within the watersheds to its estuarine systems as a way towards restoring and/or safe guarding the estuarine resources of the town.

The nature of enclosed embayments in populous regions brings two opposing elements to bear: As protected marine shorelines they are popular regions for boating, recreation, and land development; but as enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shorelines. In particular, Megansett Harbor and Squeteague Harbor (including Fiddlers Cove and Rands Harbor), as well as other embayment systems on Cape Cod, are at risk of eutrophication from increasing nitrogen loads in discharging surfacewater and groundwater from land-use changes to associated watersheds. Given their structure and access to the high quality waters of Buzzards Bay, Megansett Harbor and Squeteague Harbor currently exhibit a higher overall habitat health than most estuaries along the south shore of the Town of Falmouth and Bourne and much of Cape Cod.

The primary ecological threat to Megansett Harbor and particularly Squeteague Harbor (as it is more enclosed) marine resources is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters of the southeastern Massachusetts region has been greatly increased over the past few decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to Megansett Harbor and Squeteague Harbor and other Falmouth embayments (e.g. Fiddlers Cove, Rands Harbor, Quissett Harbor, Oyster Pond, Great Pond, Green Pond, Bournes Pond), like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. The Town of Falmouth and Bourne have been among the fastest growing towns in the Commonwealth over the past three decades and do not have centralized wastewater treatment throughout either of the two Towns. These unsewered areas contribute significantly to the nitrogen loading of the Megansett Harbor and Squeteague Harbor system, both through transport in direct groundwater discharges to estuarine waters and through limited surface water flow to the estuarine reach of each system. As existing and probable increasing levels of nutrients impact Falmouth's coastal embayments, water quality degradation will accelerate, with further harm to invaluable environmental resources.

The Towns of Falmouth and Bourne, as the primary stakeholders to the Megansett Harbor and Squeteague Harbor embayment system, have been concerned over the resource quality of the Towns significant coastal resources, inclusive of Megansett and Squeteague Harbors. The Town of Falmouth, in the mid-1980's, enacted an innovative Nutrient Overlay By-law that tied watershed development to water quality within the adjacent embayment. Nutrient limits were set for nitrogen in each of the Town's embayments. The goal was to keep nitrogen concentrations in the receiving systems below thresholds that were projected to cause water quality shifts. To acquire baseline water quality data necessary for ecological management of Falmouth's coastal salt ponds and harbors, a citizen-based water quality monitoring program was initiated by the Town of Falmouth. Falmouth Pondwatch, was established to provide on-going nutrient related embayment health information in support of the By-law. The water quality monitoring program was based on a collaborative effort between scientists, citizens and representatives of the Town of Falmouth. As originally conceived, the monitoring program focused on data collection in three initial ponds, Oyster Pond, Little Pond and Green Pond. By 1990, the scope of water quality data collection expanded to include two additional ponds, Great/Perch Pond and Bournes Pond. In 1992, the scope of data collection was once again expanded to include West Falmouth Harbor in order to evaluate the effects from a nutrient enriched wastewater plume generated by the Falmouth Wastewater Treatment Facility. Since 1997, technical aspects of the Falmouth PondWatch Program have been coordinated through the Coastal Systems Program at SMAST-UMassD. In 1992 the Buzzards Bay Project built on the Falmouth effort to put in place what is now the Coalition for Buzzards Bay's Water Quality Monitoring Program which, through its association with the Buzzards Bay Coalition and the Coastal Systems Program at UMASS-SMAST, collected data on nitrogen related water quality within the Falmouth estuaries that exist adjacent Buzzards Bay. The collaborative CBB/SMAST water quality monitoring effort covered systems such as Megansett Harbor, Fiddlers Cove and Rands Harbor System beginning in 1992. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of the embayments and harbors adjacent Buzzards Bay. The BayWatchers Program is a citizen-based water quality monitoring program run by the Coalition for Buzzards Bay (T. Williams, Project Coordinator) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD until 2008.

The common focus of the Coalition for Buzzards Bay BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the 29 embayments tributary to Buzzards Bay and determine the relationship between observed water quality and habitat health. The BayWatcher Water Quality Monitoring Program in Megansett/Squeteague Harbors, Fiddlers Cove and Rands Harbor developed a water quality baseline for these systems. Additionally, as remediation plans for various systems are implemented, the continued monitoring will help satisfy monitoring requirements by State regulatory agencies and provide baseline information to the Town of Falmouth and Bourne relative to the efficacy of remediation efforts. The MEP effort builds upon the water quality monitoring effort and includes high order biogeochemical analyses and water quality modeling necessary for developing critical nitrogen targets for the Megansett Harbor and Squeteague Harbor system. Results of the MEP analysis for Fiddlers Cove and Rands Harbor are being taken into consideration and incorporated as appropriate in the current MEP analysis of the larger Megansett Harbor and Squeteague Harbor system, to which Fiddlers Cove and Rands Harbor are tributary sub-embayments.

In conjunction with other town efforts, the Towns of Falmouth and Bourne Planning Offices continue to enhance its tools for gauging future nutrient effects from changing land-uses. The GIS database used in the present MEP evaluation is part of that continuing effort. The estuarine specific watershed based nutrient loading model, the hydrodynamic models and the water quality models being developed under the MEP for both Megansett and Squeteague Harbors will be an additional set of tools the towns can use to inform future nutrient management decisions. The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning and nitrogen management alternatives development needed by the Towns of Falmouth and Bourne. While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for the Town of Falmouth and Bourne to develop and evaluate the most cost effective nitrogen management alternatives to restore the Town's valuable coastal resources currently being degraded by nitrogen overloading.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

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

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

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

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region's coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the MassDEP with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads

(TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

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

The major Project goals are to:

- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of 70 of the embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment model available to address future regulatory needs.

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

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

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

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

Linked Watershed-Embayment Model Overview: The Model provides a quantitative approach for determining an embayment's: (1) nitrogen sensitivity, (2) nitrogen threshold loading levels (TMDL) and (3) response to changes in loading rate. The approach is fully field validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-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 Megansett/Squeteague Harbor Estuarine 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 1996, Weiskel and Howes 1992, Smith *et al.* 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). Tidal reaches within the Megansett Harbor and Squeteague Harbor system, inclusive of Fiddlers Cove and Rands Harbor, follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

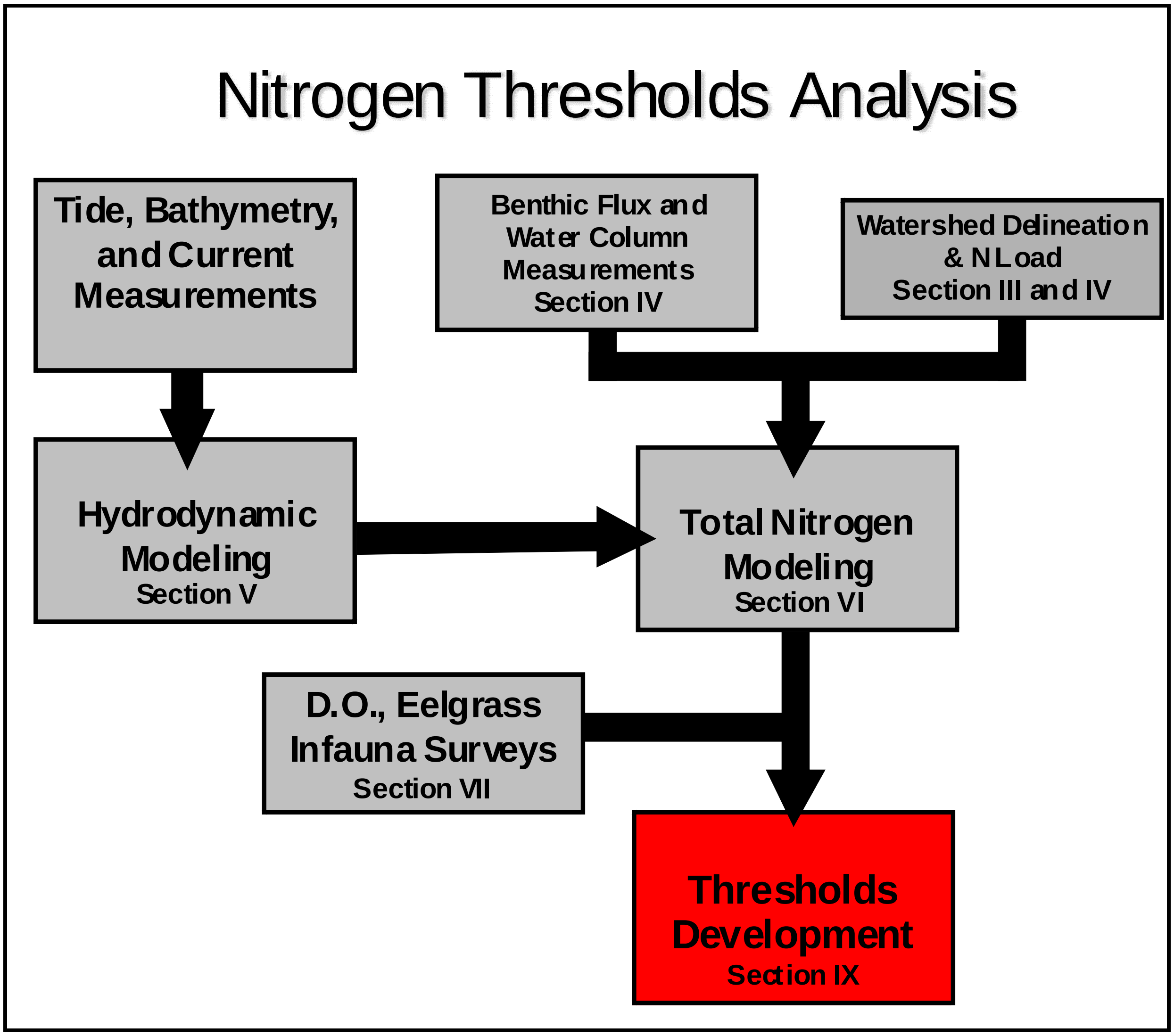


Figure I-3. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

Nutrient related water quality decline represents one of the most serious threats to the ecological health of 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 outer Megansett Harbor, Squeteague Harbor, Fiddlers Cove and Rands Harbor systems monitored by the Coalition for Buzzards Bay BayWatchers Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) to “tune” general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, the Megansett/Squeteague Harbor system appears to have reached its limit for assimilating additional nutrients without impacting ecological health while the Fiddlers Cove and Rands Harbor estuaries are presently slightly beyond the threshold for nitrogen that is supportive of ecological health. Nitrogen levels are somewhat elevated throughout the system and benthic infaunal communities are generally indicative of high quality habitat. However, there are some impaired areas and the indication of some recent eelgrass loss, but these must be assessed relative to both nutrient enrichment and other activities, such as dredging or activities related to the channel areas in the mid reaches, particularly in Squeteague Harbor. This is discussed in more detail in Section VII below. While there is no definitive record of eelgrass beds in Squeteague Harbor, there was indication that patches might have been present in 1951 (unconfirmed), but the eelgrass beds within Megansett Harbor appear to have declined along the outer fringe of the central basin in the vicinity of the inlets to Fiddlers Cove and Rands Harbor and along the northern shore of the harbor. The result is that nitrogen management of the greater Megansett Harbor system (inclusive of Fiddlers Cove and Rands Harbor), will be aimed at restoration, not protection or maintenance of existing conditions, primarily the recovery of the recently lost eelgrass habitat. In general, nutrient over-fertilization is termed “eutrophication” and when the nutrient loading is primarily from human activities, it is considered “cultural eutrophication”. Although the influence of human-induced changes has increased nitrogen loading to the system and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within a given embayment system could potentially occur without human influence and must be considered in the nutrient threshold analysis. While this finding would not change the need for restoration, it would change the approach and potential targets for management. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a “pristine” system.

I.3 WATER QUALITY MODELING

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

The MEP water quality evaluation examined the potential impacts of nitrogen loading into the Megansett Harbor and Squeteague Harbor system, taking into consideration outflow of nutrients from the Fiddlers Cove and Rands Harbor Systems. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the overall system. Once the hydrodynamic properties of each of the estuarine systems were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates in each portion of the estuarine receiving water.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models for each system were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations by USGS using a modification of the West Cape model for sub-watershed areas designated by MEP. Virtually all nitrogen entering Falmouth’s embayment systems is transported by freshwater, predominantly groundwater, either through direct discharge or after discharging to a stream flowing to estuarine waters. Concentrations of total nitrogen and salinity of Buzzards Bay / Megansett Harbor source waters and throughout Squeteague Harbor and both the Fiddlers Cove and Rands Harbor systems were taken from the BayWatchers monitoring program and from previous sampling of outer Megansett Harbor waters by MEP staff. Measurements of nitrogen and salinity distributions throughout the estuarine waters of each component of the overall system were used to calibrate and validate the water quality models (under existing loading conditions).

I.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Megansett Harbor and Squeteague Harbor system, taking into consideration MEP results generated for the Fiddlers Cove and Rands Harbor Estuarine Systems (Howes et al., 2013) in the Town of Falmouth. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed

(Section IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission data and offshore water column nitrogen values were derived from an analysis of monitoring stations in Buzzards Bay (Section IV). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Section IV. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of each embayment was performed that included a review of existing water quality information, temporal changes in eelgrass distribution, dissolved oxygen records and the results of a benthic infaunal animal analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration in a given estuarine basin. This latter assessment represents only one of many solutions and is produced to assist the Town of Falmouth and Bourne in developing a variety of alternative nitrogen management options for the Megansett Harbor and Squeteague Harbor System. Finally, any additional analyses of the two systems relative to potential alterations of circulation and flushing, including analyses to identify hydrodynamic restrictions or the effects of dredging to improve nitrogen related water quality in either Squeteague Harbor, would be presented in Section IX.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

In most marine and estuarine systems, such as the Megansett Harbor and Squeteague Harbor, inclusive of Fiddlers Cove and Rands Harbor Systems, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. As a result, there has been significant effort to develop tools for predicting how modification of watershed nitrogen loads and changes in tidal flushing quantitatively cause changes in the concentrations of water column nitrogen in the receiving estuary. Further development of these approaches generated specific guidelines as to what is to be considered acceptable water column nitrogen concentrations to achieve desired water quality goals (e.g., see Cape Cod Commission 1991, 1998; Howes et al. 2002).

These tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. In contrast, some approaches can be tailored for each individual estuary of interest, but require large amounts of site-specific information and therefore are not generally applied. The present Massachusetts Estuaries Project (MEP) effort uses one such site-specific approach. The assessment focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species within individual estuaries. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for the specific set of conditions in each of the coastal embayments of southeastern Massachusetts, including the Megansett Harbor and Squeteague 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.

Few studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Megansett Harbor and Squeteague Harbor System over the past three decades to help inform the MEP process. Indirectly supporting the present Massachusetts Estuaries Project effort to develop a nitrogen threshold for Megansett Harbor and Squeteague

Harbor was a historic investigation of eelgrass in Dr. Joseph Costa's Ph.D. Thesis which provided a point of comparison to assess habitat conditions at a time when nutrient loading was likely less than at present. Dr. Costa's dissertation provided a detailed description of the present day (1988) distribution of eelgrass in Buzzards Bay and he estimates the contribution of eelgrass growth to productivity in Buzzards Bay. Additionally, Dr. Costa investigates the effects of the occurrence of the wasting disease of 1931-32 that destroyed virtually all eelgrass in the region. In his dissertation he documents the wasting disease related decline and other declines due to disease by analyzing eelgrass seed deposition in sediment cores. Of particular interest to the MEP are specific "case histories" of changing eelgrass abundance that involve natural and anthropogenic disturbances such as storms, ice scour and freezing, and pollution.

Additionally, a study focused on relating water quality, nutrient pollution and ascidian diversity in coastal waters of southeastern Massachusetts loosely helped inform the MEP development of nutrient thresholds in both Megansett and Squeteague Harbors (Carmen et al., 2007). Combining high level estuarine data collection under the MEP with quantitative information on water column parameters over multiple summers (including nitrogen) described below and MassDEP surveys of eelgrass distribution in outer and inner Megansett Harbor has enabled the development of the embayment specific thresholds described in Section VIII of this report.

Cape Cod Surface Water Management Study. 2002. Cape Cod Commission (Eichner, E.M., S.C. Michaud, T.C. Cambareri, B. Smith, and G. Prahm).
Study included watershed nitrogen loading analyses for Barnstable Harbor, Pocasset Harbor, and Megansett Harbor. Study contains watershed delineations, results of county-funded tidal flushing analysis of Pocasset and Megansett Harbors, and an application of the Buzzards Bay Project nitrogen loading limits based on the flushing study. Indicated that existing and buildout loads exceeded the most sensitive/ORW BBP standards for Rands Harbor and Fiddlers Cove, but only exceeded the SA standard for buildout in Rands Harbor. Watershed loading for the combined Megansett Harbor and Squeteague Harbor subwatershed did not exceed their respective BBP standards. Identified potential strategies to meet ORW standard based on existing watershed loading in Rands Harbor watershed were: a) no wastewater discharge and b) 90% reduction in wastewater and 50% reduction in fertilizer loads. Identified potential strategies to meet ORW standard based on existing watershed loading in Fiddlers Cove watershed were: a) 26% reduction in wastewater and b) 17% reduction in wastewater and 50% reduction in fertilizer loads. Recommendation included refinement of these analyses under the Massachusetts Estuaries Project, which had just started during this study's preparation.

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

The common focus of the Buzzards Bay Coalition BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay to support evaluations of observed water quality and habitat health. The BayWatcher Water Quality Monitoring Program in Megansett and Squeteague Harbors as well as the Fiddlers Cove and Rands Harbor Embayment Systems developed a data set that elucidated the long-term water quality of this system (Figure II-1). The monitoring undertaken was a collaborative effort with the Coalition (Tony Williams) coordinating the field effort and chemical assays being completed by the SMAST Coastal Systems Analytical Facility until 2008. 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 are a prerequisite for entry into the MEP. Implementation of the MEP's Linked Watershed-Embayment Approach necessarily incorporates the quantitative water column nitrogen data (1999-2009) gathered by the Monitoring Program and watershed and embayment data collected by MEP staff.

Since the results of the long term Water Quality Monitoring Program (1999-2009) and initial habitat assessments, suggest that that portions of the Megansett and Squeteague Harbor Embayment Systems are presently beyond their 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 each of the Harbor basins and to develop nutrient thresholds to guide the Town's estuarine management planning relative to restoration of the Megansett Harbor and Squeteague Harbor estuaries.

Regulatory Assessments of Megansett Harbor and Squeteague Harbor Resources - In addition to locally generated studies, Megansett Harbor and Squeteague Harbor are part of the Commonwealth's environmental surveys to support regulatory needs. Both the Megansett and Squeteague Harbors contain a variety of marine resources of value to the citizens of Falmouth and Bourne 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 Chapter 7 to support the nitrogen thresholds analysis. For the Megansett Harbor and Squeteague Harbor Estuaries these include:

- Designated Shellfish Growing Area – MassDMF (Figure II-2)
- Shellfish Suitability Areas – MassDMF (Figure II-3)
- Anadromous Fish Runs - MassDMF (Figure II-4)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-5)
- Mouth of Coastal Rivers – MassDEP Wetlands Program (NOT APPLICABLE)

The MEP effort builds upon earlier watershed delineations by the Cape Cod Commission and land-use analyses by the Buzzards Bay Project, 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 critical nitrogen thresholds for nitrogen management planning of the Fiddlers Cove and Rands Harbor Estuarine

Systems. The MEP has incorporated appropriate and available data from pertinent previous studies to enhance the determination of nitrogen thresholds for the Fiddlers Cove and Rands Harbor Systems and to reduce costs to the Town of Falmouth.

Figure II-1. Coalition for Buzzards Bay Water Quality Monitoring Program for Megansett Harbor and Squeteague Harbor. Estuarine water quality monitoring stations sampled by the Coalition and analyzed by SMAST staff during summers 1999 to 2009. A nutrient and oxygen station exists in both Fiddlers Cove (FC-1) and Rands Harbor (RH-1). The location of those stations is provided in the Fiddlers / Rands MEP Report as well as through the Buzzards Bay Coalition web site.

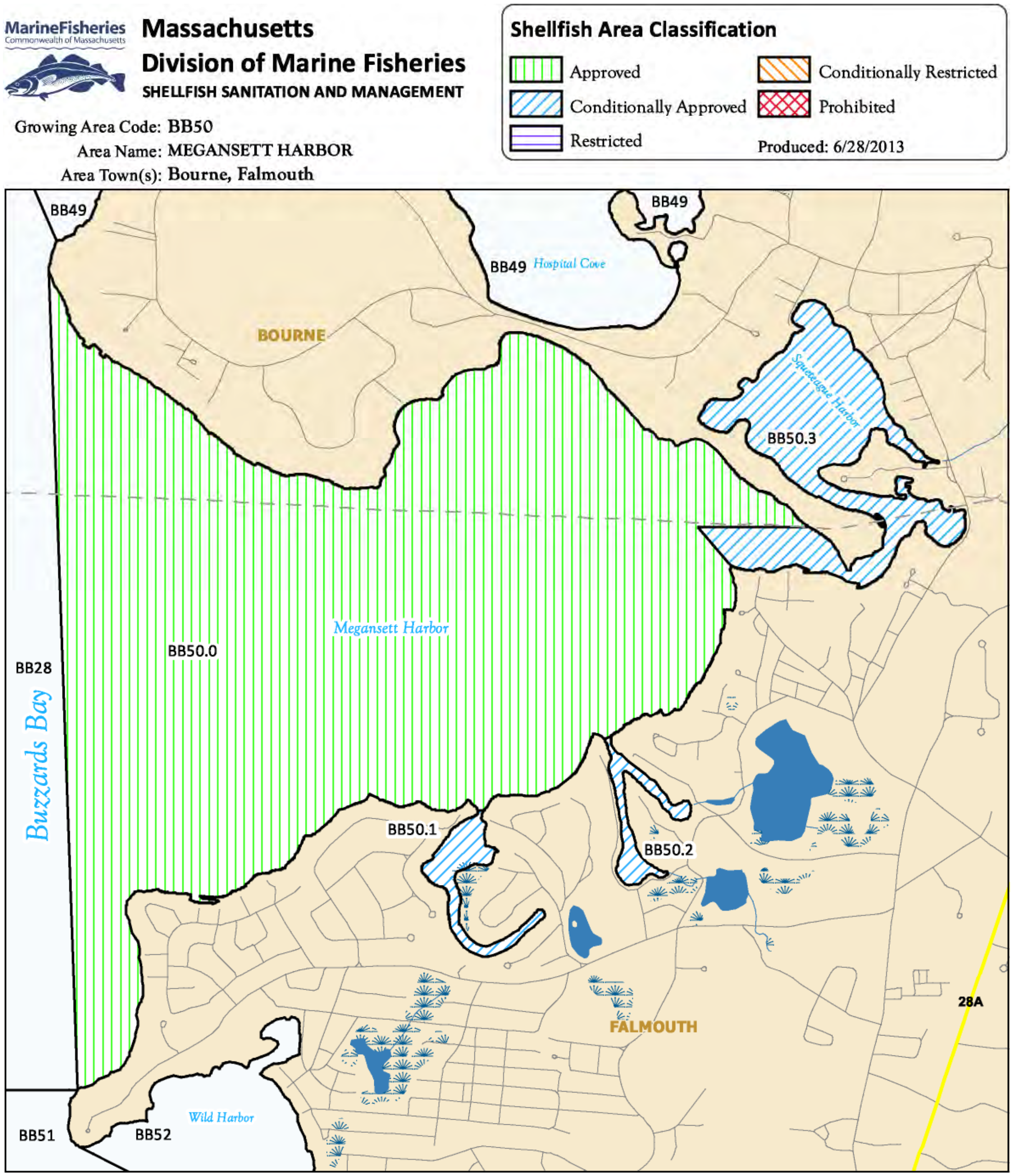


Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

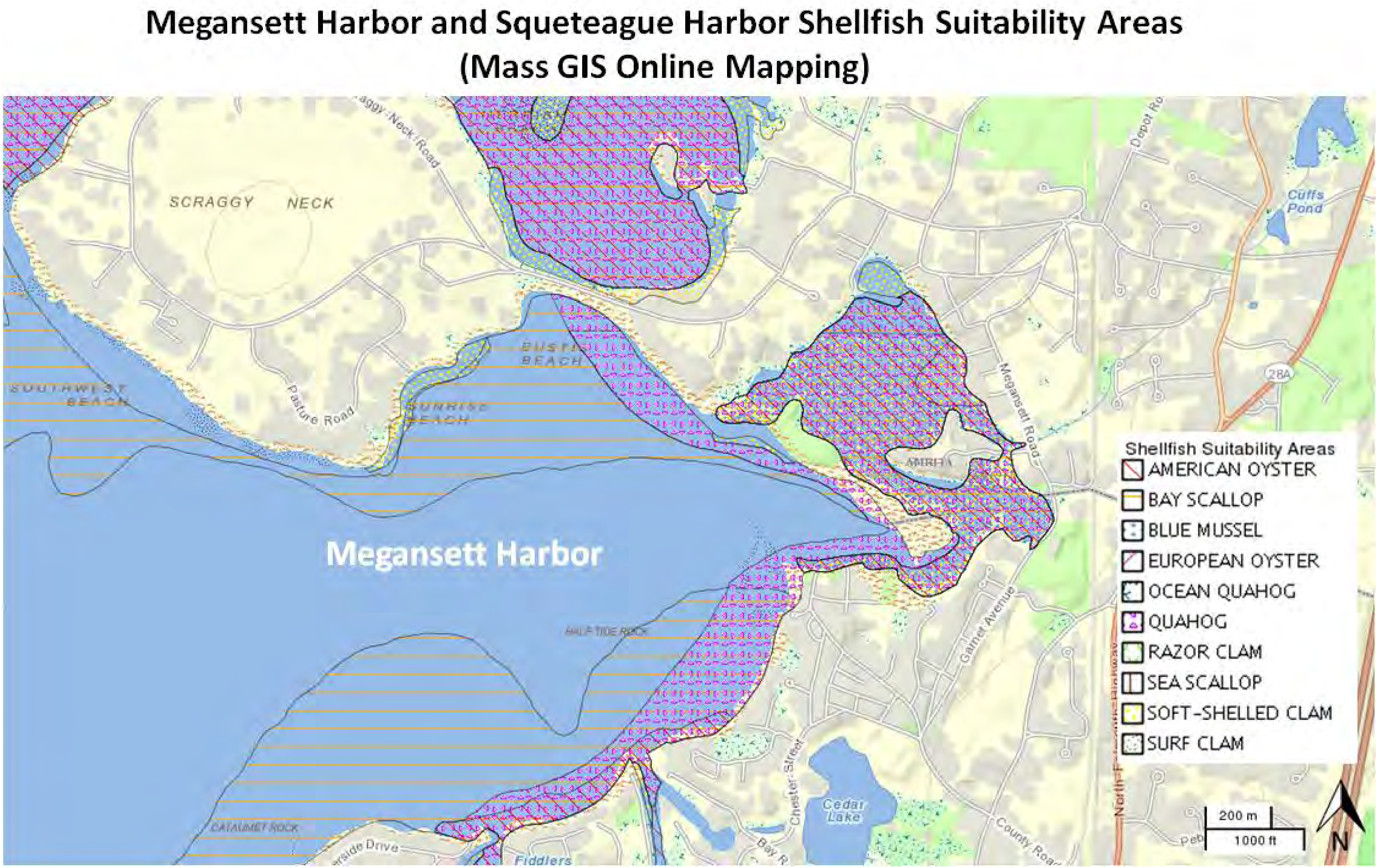


Figure II-3. Location of shellfish suitability areas within the Megansett Harbor and Squeteague Harbor estuary system as determined by the Massachusetts Division of Marine Fisheries. Suitability does not necessarily mean "presence".

Megansett Harbor and Squeteague Harbor Anadromous Fish Presence
(Mass GIS Online Mapping)

Figure II-4. Anadromous fish runs within the Megansett Harbor and Squeteague Harbor estuary system as determined by Massachusetts Division of Marine Fisheries. The red diamonds show areas where fish were observed. There are no anadromous fish runs in Fiddlers Cove or Squeteague Harbor.

Megansett Harbor and Squeteague Harbor NHESP Priority Habitats of Rare Species (Mass GIS Online Mapping)

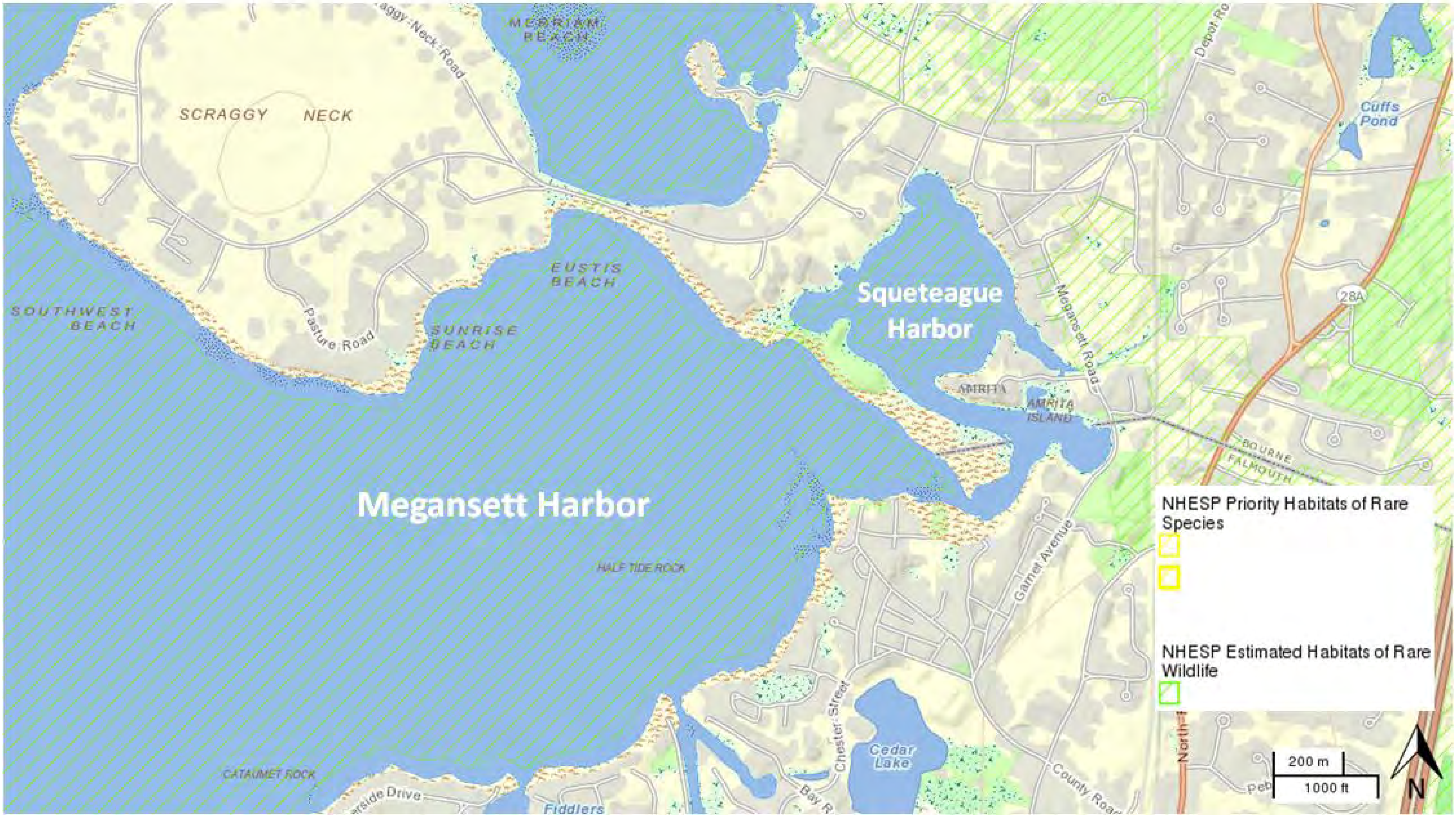


Figure II-5. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Megansett Harbor and Squeteague Harbor estuary system as determined by - NHESP.

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 Megansett and Squeteague Harbors. The Megansett and Squeteague Harbors watershed is mostly split between the Towns of Falmouth and Bourne with a large portion of the upper watershed within Joint Base Cape Cod (JBCC). A portion of the uppermost watershed within JBCC is within the Town of Sandwich.

In the present investigation, the USGS was responsible for the application of its groundwater modeling approach to initially define the watershed or contributing area to the Megansett and Squeteague Harbors under evaluation by the Project Team. The Squeteague Harbor portion of the combined system is a 0.33 square kilometer, shallow basin formed behind a barrier beach with a single inlet to Megansett Harbor. Megansett Harbor has direct and open interface to Buzzards Bay between Scraggy Neck to the north and Nyes Neck to the south. Fiddlers Cove and Rands Harbor, which were previously assessed in a combined MEP nutrient threshold analysis (Howes et al., 2013), are located along the southern shore of Megansett Harbor. Watershed modeling was undertaken to sub-divide the overall watershed to the Megansett and Squeteague Harbors system into functional sub-units based upon: (a) defining inputs from contributing areas to each major portion within 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 travel-time distributions within subwatersheds 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 has also been used to evaluate the contributing areas to public water supply wells in the regional Sagamore flow cell on Cape Cod; the Megansett and Squeteague Harbors watershed is located along the western edge of the Sagamore groundwater lens. USGS model outputs were also compared to surface water discharges measured as part of the MEP stream flow program (2005 to 2006) and 2010-2013 well pumping rates from the Bourne Water District (personal communication, Bob Profit, BWD Superintendent).

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 streams and the portion of the groundwater system that discharges directly into an estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Megansett and Squeteague Harbors system and its various subwatersheds, such as Osborne Pond and Squeteague Stream, 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, 1994), 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 Megansett and Squeteague Harbors system and its subwatersheds 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 USGS 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 the Megansett and Squeteague Harbors watershed area, the groundwater model included bedrock at depths approximately 100 to 150 feet below NGVD 29 (Walter and Whealan, 2005). More refined recent bedrock mapping has generally confirmed these depths (Fairchild et al., 2012). In the groundwater flow model, the bedrock depths mean that the lowest model layer is inactive throughout most of the watershed area. 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 also varies in elevation depending on the location within the lens.

Direct rainwater run-off in these Cape Cod aquifer materials is typically rather low. Lithological 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 available stream flows. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Towns and stream flow data collected in 1989-1990 as well as 2003.

The 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 easternmost portions of the Megansett and Squeteague Harbors system watershed are located in the Mashpee Outwash Plains Deposits, while the westernmost portions, closer to the estuaries are located in the Moraine Outwash. In between these two deposits, and comprising the bulk of the watershed, are the Buzzards Bay Moraine (sometimes called Falmouth Moraine) Deposits (Oldale and Barlow, 1986). The moraine deposits were created during a re-advance of the regional lobes of the continental ice sheet that excavated and piled up previously deposited materials resulting in a mix of sands, clays, and gravels, while the outwash deposits generally were deposited in layers of well-sorted materials as rivers flowed away from the edges of the ice sheet. Glacial collapse structures caused by melting of remnant ice blocks formed the kettlehole depressions that are now freshwater ponds. Although the watershed glacial materials vary, modeling and field measurements of contaminant transport at the Joint Base Cape Cod (formerly Massachusetts Military Reservation) have shown that groundwater flowpaths are largely unaffected by the transitions between outwash and moraine materials (*e.g.*, Masterson, *et al*., 1996).

The regional USGS 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 MEGANSETT AND SQUETEAGUE HARBORS SYSTEM CONTRIBUTORY AREAS

The initial watershed and sub-watershed boundaries for the Megansett and Squeteague Harbors embayment system, including Osborne Pond and the BWD water supply wells were modeled by the United States Geological Survey (USGS). Model outputs of the watershed boundaries are usually presented as “saw toothed” lines that reflect the movement of modeled particles between the grid cells that make up the groundwater model and how those cells are organized to reflect natural features, such as pond shorelines, wetlands, river segments, and contributing areas to public water supplies. These modeled lines were then “smoothed” to produce a more natural boundary used for the MEP watersheds. The smoothing includes evaluations to: (a) correct for the model grid spacing, (b) to reflect actual pond and coastal shorelines based on aerial maps, (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 (2005-2006). The smoothing efforts were 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, subwatersheds to public water supply wells, and the one MEP stream gauge within the overall watershed. Overall, 13 sub-watershed areas were delineated within the Megansett and Squeteague Harbors study area with an additional 20 previously delineated subwatersheds to Rands Harbor and Fiddlers Cove (Howes et al., 2013), which are located along the southern shore of Megansett Harbor (Figure III-1).

Table III-1 provides the daily freshwater discharge volumes for the subwatersheds as calculated from the MEP watersheds; these volumes were used in the salinity calibration of the MEP water quality 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 Megansett and Squeteague Harbors system from the MEP delineated watershed is 29,886 m3/d. This flow includes balanced corrections for flow removed from the watershed by the BWD wells and returned within the watershed by measured public water use on individual parcels.

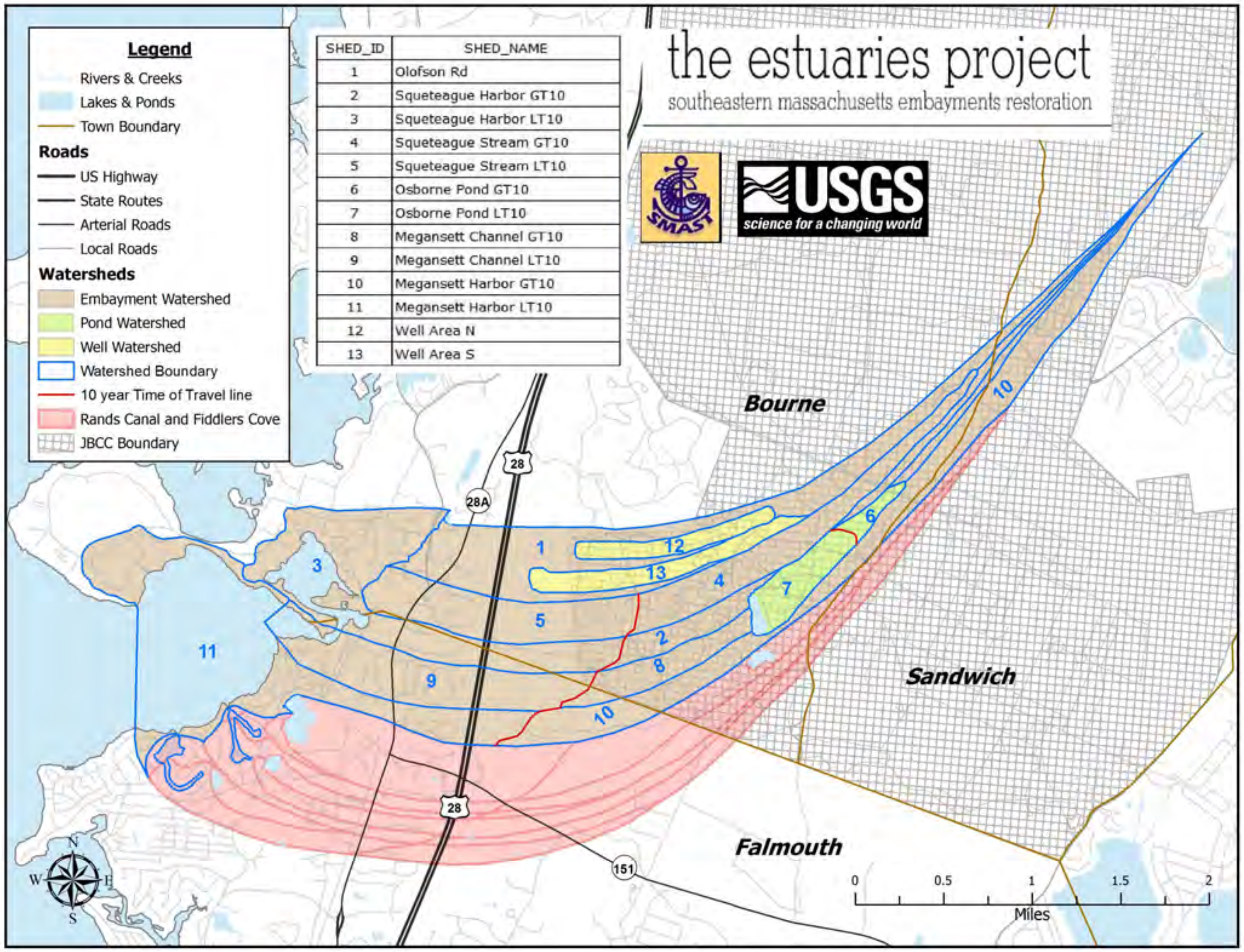


Figure III-1. Watershed delineation for the Megansett and Squeteague Harbors Estuarine System, which exchanges tidal waters with Buzzards Bay. Subwatershed delineations are based on USGS groundwater model output with modifications to better address pond and estuary shorelines and MEP stream gauge measurements. Ten-year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names. Watersheds to Rands Harbor and Fiddlers Cove are part of the Megansett Harbor watershed and were delineated in a previous MEP assessment (Howes et al., 2013).

Table III-1. Daily groundwater discharge from each of the sub-watersheds in the watershed to the Megansett and Squeteague Harbors system estuary, as determined from the MEP watersheds and corrected return flow from public water supply wells.

Watershed	#	Watershed Area (acres)	% contributing to Estuaries	Discharge	
				m^3/day	ft^3/day
Olofson Road	1	421	100%	3,254	114,914
Squeteague Hbr GT10	2	123	100%	943	33,302
Squeteague Hbr LT10	3	373	100%	2,991	105,626
Squeteague Stream GT10	4	211	100%	1,616	57,069
Squeteague Stream LT10	5	238	100%	1,877	66,286
Osborne Pond GT10	6	23	100%	179	6,321
Osborne Pond LT10	7	93	100%	715	25,250
Megansett Channel GT10	8	137	100%	1,050	37,080
Megansett Channel LT10	9	254	100%	2,063	72,854
Megansett Hbr GT10	10	398	100%	3,052	107,780
Megansett Hbr LT10	11	313	100%	2,616	92,383
BWD_Well N	12	69	16%	0	0
BWD_Well S	13	101	16%	0	0
Rands Harbor	MEP	1,008	100%	7,737	273,230
Fiddlers Cove	MEP	234	100%	1,792	63,284
TOTAL MEGANSETT AND SQUETEAGUE HARBORS SYSTEM				29,885	1,055,380

Notes:
1) Discharge volumes are based on 27.25 inches of annual recharge on watershed areas plus adjustments to account for addition or subtraction of measured public water use within the subwatersheds. Watershed areas are unadjusted.
2) Bourne Water District Wells watershed area based on average pumping rates at the time of the USGS groundwater modeling; 16% of pumped water is returned within the overall watershed based on measured water uses that are also located within the Town of Bourne. Review of more recent BWD pumping rates (2010-2014) are in reasonable balance with rates used for USGS modeling. The 16% return flow is distributed to the appropriate subwatersheds. No parcels within the Well subwatersheds have public water connections, so no discharge is assigned to these subwatersheds.
3) Squeteague Stream subwatersheds (#4 & #5) discharge into Squeteague Harbor at the location of the MEP stream gauge. Estimated flow from these subwatersheds reasonably matches MEP average flow at this location. This is discussed in Section IV.2.
4) Rands Harbor and Fiddlers Cove watershed flows are based on information in their MEP report (Howes et al., 2013).
5) listed flows do not include precipitation on the surface of the estuary
6) totals may not match due to rounding.

The MEP watershed delineation is the second watershed delineation completed in recent years for the Megansett and Squeteague Harbors System. Figure III-2 compares the delineation completed under the current effort with the delineation completed by the Cape Cod Commission (Eichner, *et al*., 2002). The CCC delineation was largely based on local and regional water table measurements collected from available well data, including some of the same data used in the USGS groundwater model, over a number of years and normalized to average conditions. The Commission's delineation was incorporated into the Commission's regulations through three versions of the Regional Policy Plan (CCC, 1996, 2001, and 2009).

The MEP watershed area for the Megansett and Squeteague Harbors system as a whole is 16% larger than 2002 CCC delineation (4,560 acres vs. 3,810 acres, respectively). These areas include the estuary surface area. The sources of the area difference are the location of the southern boundaries of Rands Harbor and Fiddlers Cove watersheds and a regional groundwater divide further to the east. The northern boundary to Megansett and Squeteague Harbors is approximately in the same location, but the southern boundary to Rands Harbor is approximately 0.8 km further south in the MEP watershed. This location shift combined with another shift of approximately 0.5 km east in the regional groundwater divide (*e.g.*, the divide between groundwater discharging to Buzzards Bay or Vineyard Sound) creates a wider north/south cross-section and a longer watershed "tail" compared to the CCC watershed. In addition to these changes, the MEP watershed delineation also includes delineation of interior sub-watersheds to various components of the Megansett and Squeteague Harbors estuarine system, such as selected 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).

The MEP watersheds compared favorably with both measured streamflow and pumping rates from public water supply wells. MEP staff gathered streamflow in Squeteague Stream, which discharges into Squeteague Harbor (detailed in Section IV.2). Review of aerial photographs showed a surface water channel from the cranberry bogs north of Long Pond in Bourne, into Long Pond, out of Long Pond, and connected to Squeteague Stream. Measured flow in Squeteague stream was found to be less than predicted flows using MEP/USGS groundwater modeling. Comparison of the measured flow to the model results suggested that recharge to only subwatersheds #4 and #5 matched the measured flows. A similar comparison of the model results to measured pumping rates between 2010 and 2013 from Bourne Water District Wells #2 and #5 shows that the contributing areas are somewhat larger than average pumping rates, but are a reasonable match for the maximum annual rates during the four year period. This type of comparison between measured and modeled information is another step to reinforce the reliability of the watershed delineations.

The evolution of the watershed delineations for the Megansett and Squeteague Harbors 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. Evaluation of older data and incorporation of new data during development of the model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model and the use of this model for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon 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 Megansett and Squeteague Harbors system (Section V.1).

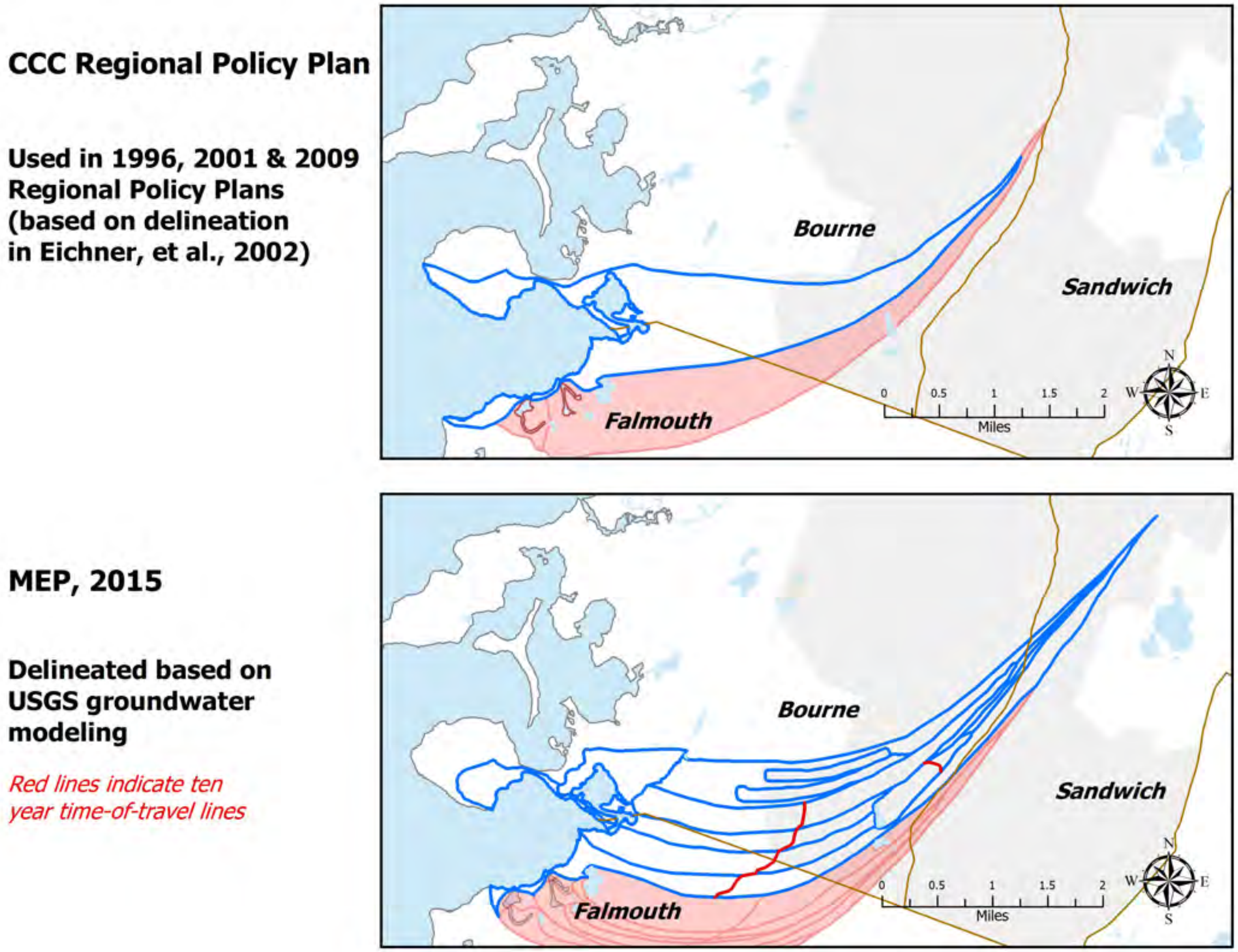


Figure III-2. Comparison of MEP Megansett and Squeteague Harbors watershed and sub-watershed delineations used in the current assessment and the prior Cape Cod Commission watershed delineation (Eichner and others, 2002), which had been used in three Barnstable County Regional Policy Plans (CCC, 1996, 2001, 2009). The MEP watershed area for the Megansett and Squeteague Harbors system as a whole is 16% larger than CCC delineation. Megansett and Squeteague Harbors exchange tidal waters with Buzzards Bay to the west.

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

Management of nutrient related water quality and habitat health in coastal waters requires determination of the amount of nitrogen transported by freshwaters (surface water flow, groundwater flow) from the surrounding watershed to the receiving embayment of interest. In southeastern Massachusetts, the nutrient of management concern for estuarine systems is nitrogen and this is true for the Megansett/Squeteague Harbor Estuarine System. Nitrogen inputs sourced within the watershed 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 aquatic 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 itself, 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 Megansett and Squeteague Harbors estuary system, the MEP Technical Team developed nitrogen-loading rates (as described in this section) to each component of the estuary and its associated watersheds (Section III). The Megansett and Squeteague Harbors watershed was sub-divided to define contributing areas or subwatersheds to each of the major inland freshwater systems, public water supply wells, 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 13 subwatersheds were delineated in the Megansett and Squeteague Harbors watershed, including watersheds to Osborne Pond, the two Bourne Water District (BWD) public water supply wells, and the MEP gauged stream (see Chapter III). The Megansett Harbor watershed also includes an additional 20 previously delineated subwatersheds to Rands Harbor and Fiddlers Cove (Howes et al., 2013), which are located along the southern shore of Megansett Harbor.

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 review involves a temporal review of land use changes, the time of groundwater travel subwatersheds 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 subwatersheds in the Megansett and Squeteague Harbors watershed have been delineated for ponds, streams and the estuary itself. Review of less than 10 year and greater than 10 year travel time watersheds indicates that 96% of the unattenuated nitrogen load from the whole watershed is within less than 10 year travel time to the estuary (Table IV-1). This review indicates that the measured water quality within the estuarine basins should be in equilibrium with the nitrogen loading from the watershed. MEP staff also traditionally reviews the age of single family residences in the greater than 10 year subwatersheds in order to further confirm the balance between measured water quality in the estuary and watershed nitrogen loads. This review of year-built information typically relies on information in the town assessor's databases. Within this watershed, there are no single family residences listed in the town databases within the greater than 10 year subwatersheds; all land in these subwatersheds is part of Joint Base Cape Cod (JBCC) or is undeveloped. JBCC lands include a significant number of residential units and other buildings, but MEP staff was unsuccessful in multiple attempts to confirm the dates of construction of these units. However, review of available Google Earth aerial photographs show all of the current buildings in the watershed existed prior to 1991. The overall result of the timing of development relative to groundwater travel times (including the GT10 subwatersheds) 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 subwatersheds is not important for modeling existing watershed nitrogen loading conditions. Overall and based on the review of all this information, it was determined that the Megansett/Squeteague Harbor Estuarine System is currently in balance with its watershed load.

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is 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 subwatershed-specific land uses and pre-determined nitrogen loading rates based on regional analyses. For the Megansett and Squeteague Harbors estuary system, the model used Town of Falmouth and Town of Bourne land-use data that is transformed into nitrogen loads using both regional nitrogen loading factors and local watershed-specific data (such as parcel-by-parcel water use). Determination of the nitrogen loads required obtaining watershed-specific information regarding wastewater, 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 within surface waters is included at a later stage.

Natural attenuation of nitrogen during transport from land-to-sea within the Megansett and Squeteague Harbors watershed was determined based upon a site-specific study of streamflow and attenuation in the upgradient freshwater ponds. Streamflow was characterized at a Megansett Road gauge that discharges to Squeteague Harbor. Subwatersheds to this stream discharge point allowed comparisons between field collected stream data and estimates from the nitrogen-loading sub-model. Nitrogen attenuation in individual ponds is generally estimated based on available information. Attenuation through the ponds is conservatively assumed to equal 50% unless available monitoring and pond physical data is reliable enough to calculate a pond-specific attenuation factor. Streamflow and associated surface water attenuation is included in the MEP's nitrogen attenuation and freshwater flow investigation, presented in Section IV.2.

Table IV-1. Percentage of unattenuated nitrogen loads in less than ten year time-of-travel subwatersheds to Megansett and Squeteague Harbors.

WATERSHED		LT10	GT10	TOTAL	%LT10
Name		kg/yr	kg/yr	kg/yr	
Olofson Road	1	464		464	100%
Squeteague Hbr GT10	2		99	99	0%
Squeteague Hbr LT10	3	1,621		1,621	100%
Squeteague Stream GT10	4		121	121	0%
Squeteague Stream LT10	5	1,300		1,300	100%
Osborne Pond GT10	6		8	8	0%
Osborne Pond LT10	7	84		84	100%
Megansett Channel GT10	8		61	61	0%
Megansett Channel LT10	9	1,268		1,268	100%
Megansett Hbr GT10	10		144	144	0%
Megansett Hbr LT10	11	2,389		2,389	100%
BWD_Well N	12	35		35	100%
BWD_Well S	13	39		39	100%
Combined Estuary Surface		2,415		2,415	100%
Cedar Lake	MEP	686	70	755	91%
Rands Harbor System	MEP	2,154	365	2,519	86%
Fiddlers Cove System	MEP	1,323	341	1,664	80%
Megansett and Squeteague Harbors Whole System		13,776	1,208	14,985	92%

Notes:

a) Whole system totals may not add due to rounding.
b) Cedar Lake, Rands Harbor System, and Fiddlers Cove System loads are from Rands Harbor/Fiddlers Cove MEP Assessment (Howes et al., 2013).
c) Loads have not been adjusted to account for removal/return flow from BWD wells. The total combined nitrogen load within the well subwatersheds is 0.5% of the total watershed load.
d) Loads include atmospheric loading on the estuary surface waters; if atmospheric loading on the surface of the estuary is excluded the percentage of load within a less than 10 year time-of-travel decreases to 90%.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. In the present effort, one new freshwater pond has delineated subwatersheds within the Megansett and Squeteague Harbors watershed: Osborne Pond. Four other ponds in the previously assessed Rands Harbor watershed are also included in the overall Megansett and Squeteague Harbors watershed: Edmunds Pond, Cedar Lake, Flax Pond, and Trout Pond (Howes et al., 2013). 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 subwatersheds 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 Megansett and Squeteague Harbors 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 Megansett and Squeteague Harbors is shared among the Towns of Falmouth, Bourne, and Sandwich, Estuaries Project staff obtained digital parcel and tax assessor's data from the towns to serve as a base for the watershed nitrogen loading model. Digital parcels and land use/assessors data are from 2012, 2012, and 2010, respectively. Using GIS techniques, these data were linked to three years of individual account water use data from Falmouth (2008-2010) and Bourne (2009-2011). All Sandwich parcels are located within Joint Base Cape Cod (JBCC), so no water use is assigned to these parcels. The resulting unified town assessor/water use database also contains traditional information regarding land use classifications (MassDOR, 2015) plus additional information developed by the towns. The database efforts were completed with the assistance from GIS staff from the Cape Cod Commission (CCC).

Figure IV-1 shows the land uses within the Megansett and Squeteague Harbors estuary watershed. Land uses in the study area are grouped into ten land use categories: 1) residential, 2) commercial, 3) industrial, 4) agricultural, 5) mixed use, 6) undeveloped, 7) public service/government, including road rights-of-way, 8) woodland, 9) freshwater ponds and 10) properties without town assessor's land use codes. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MassDOR, 2015). "Public service" in the MassDOR system is tax-exempt properties, including lands owned by government (*e.g.*, wellfields, schools, open space, roads) and private groups like churches and colleges.

Public service land uses are the dominant land use type in the overall Megansett and Squeteague Harbors watershed and occupy 73% of the watershed area (Figure IV-2). The majority of the public service lands in the Megansett and Squeteague Harbors watershed are part of the JBCC, which is located east of Route 28 and covers most of the GT10 subwatersheds. Within the portion of the JBCC within the watershed are residential units, the former base landfill, and other portions of the cantonment area. Other public service lands within the watershed, which are typically in the LT10 subwatersheds, include: town Conservation Commission lands, Bourne Water District properties, and other state owned lands. Residential land uses occupy the second largest area with 19% of the overall watershed area. It is notable that land classified by the town assessor as undeveloped is 5% of the overall watershed area.

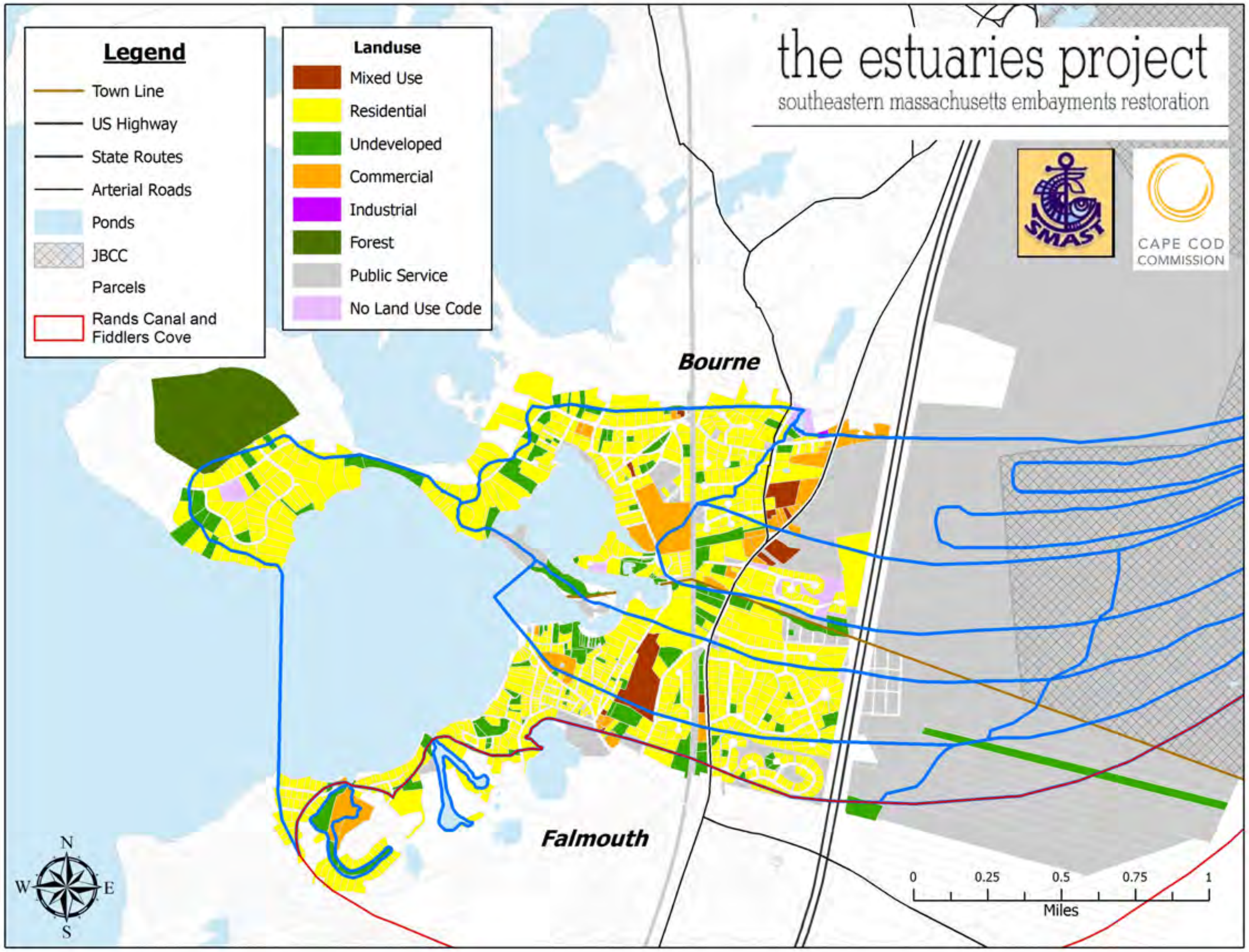


Figure IV-1. Land-use in the Megansett and Squeteague Harbors system watershed and subwatersheds. The overall watershed is shared among the towns of Bourne, Falmouth, and Sandwich and includes Joint Base Cape Cod. Land use classifications are based on town assessor classifications and MADOR (2015) categories. Assessor and parcel data used in this map and the MEP land use evaluation are from the year 2012. The eastern portions of the watershed are all within JBCC and are all one parcel.

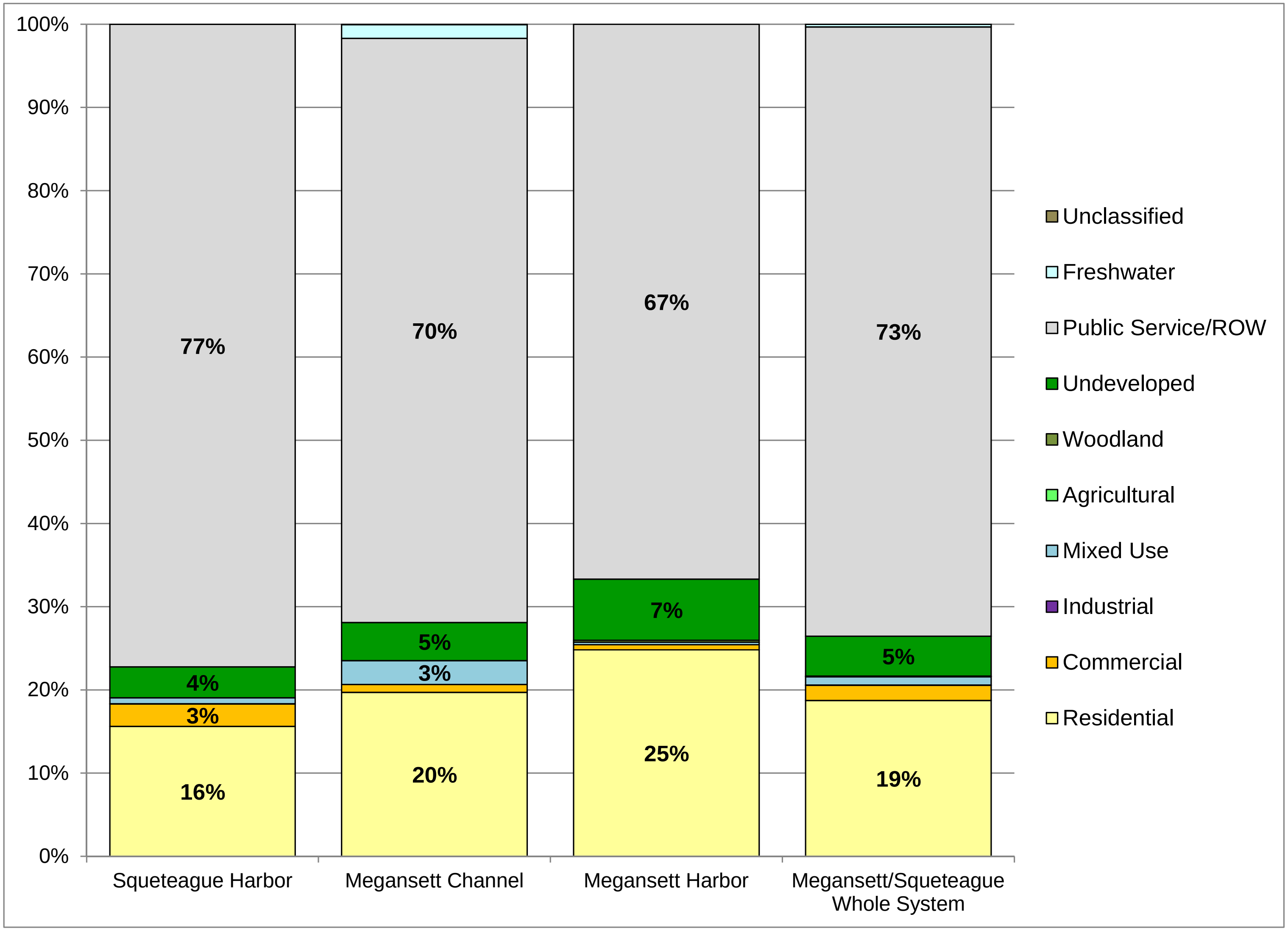


Figure IV-2. Distribution of land-uses by area within the Megansett and Squeteague Harbors system watershed and component subwatershed groups. Land use categories are generally based on town assessor's land use classification and grouping recommended by MADOR (2015). Unclassified parcels do not have an assigned land use code in the town assessor's databases. Only percentages greater than or equal to 3% are labeled.

Although the majority of the watershed area is public service land uses, the dominant parcel type in all of the subwatershed groupings is residential land uses. Residential parcels are 67% of the total parcel count in the Squeteague Harbor subwatershed, 72% of parcels in the Megansett Channel subwatershed, 78% of the parcels in the Megansett Harbor subwatershed, and 72% of all parcels in the overall Megansett and Squeteague Harbors system watershed.
Single-family residences (MassDOR land use code 101) are the dominant type of residential parcel; these represent 80% to 100% of all residential parcels in the individual subwatersheds, 95% of the residential parcels in the overall Megansett and Squeteague Harbors system watershed, and 94% of the residential parcel area in the overall watershed. The average single family residence parcel area is 26,457 sq ft.

In order to estimate wastewater flows within the Megansett and Squeteague Harbors study area, MEP staff also obtained parcel-by-parcel water use data from the Town of Falmouth and the Bourne Water District. All Sandwich parcels are located within JBCC, so no water use is assigned to these parcels. Three years of individual account water use data was obtained for Bourne (2009-2011) and three years was obtained for Falmouth (2008-2010). The combined Falmouth water use and parcel database was obtained from the Town of Falmouth (personal communication, Bob Shea, GIS Coordinator, 11/10). This same database has been used in other MEP assessments, including the Rands Harbor/Fiddlers Cove assessment (Howes et al., 2013). The Town of Bourne parcels and Bourne Water District water use databases were combined by the CCC GIS staff.

Measured water use is used to estimate wastewater-based nitrogen loading from individual parcels; average water use is used for each parcel with multiple years of data. The final wastewater nitrogen load for each parcel is based upon the measured water-use, wastewater nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2). All parcels are assumed to use on-site septic systems unless additional information is available. It is assumed that all JBCC buildings are connected to the JBCC wastewater treatment facility.

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. 1988, Weiskel & Howes 1991, 1992, Koppelman 1978, Frimpter *et al.* 1990, Brawley *et al.* 2000, Howes et al., 2000, Costa *et al.* 2002). Variation in *per capita* nitrogen load has been found to be relatively small, with average annual *per capita* nitrogen loads generally between 1.9 to 2.3 kg person-yr^{-1}.

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

All nitrogen losses within septic systems are incorporated into the MEP analysis. For example, information developed at the Massachusetts 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.,* 2002). Downgradient 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 times N concentration) of 23.63, to convert water (per volume) to nitrogen load (N mass). This coefficient uses a *per capita* nitrogen load of 2.1 kg N person-yr^{-1} and is based upon direct measurements and corrects for changes in concentration that result from *per capita* shifts in water-use (*e.g.*, due to installing low plumbing fixtures or high versus low irrigation usage).

The nitrogen loads developed using this approach have been validated in a number of long and short term field studies where integrated measurements of nitrogen discharge from watersheds could be directly measured. Weiskel and Howes (1991, 1992) conducted a detailed watershed/stream tube study that monitored septic systems, leaching fields and the transport of the nitrogen in groundwater to adjacent Buttermilk Bay. This monitoring resulted in estimated annual per capita nitrogen loads of 2.17 kg (as published) to 2.04 kg (if new attenuation information is included). Further, modeled and measured nitrogen loads were determined for a small 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 has limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water used based on average residential occupancy to measured average water uses. This is performed as a quality assurance check to increase certainty in the final results. This comparison has shown that the larger the watershed the better the match between average water use and occupancy. For example, in the cases of the combined Great Pond, Green Pond and Bournes Pond watershed in the Town of Falmouth and the Popponesset Bay/Eastern Waquoit Bay watershed, both of which cover large areas and have significant year-round populations, the septic nitrogen loading based upon the census data is within 5% of that from the water use approach. This comparison matches some of the variability seen in census data itself. Census blocks, which are generally smaller areas of any given town, have shown up to a 13% difference in average occupancy from town-wide occupancy rates. These analyses provide additional support for the use of the water use approach in the MEP study region.

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

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

In order to provide an independent validation of the average residential water use within the Megansett and Squeteague Harbors watershed, MEP staff reviewed US Census population values for the Towns of Falmouth and Bourne. 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 2010 US Census, average occupancy within Falmouth is 2.24 people per housing unit with 64% of year-round occupancy of available housing units, while average occupancy in Bourne is 2.51 people per housing unit with 73% of year-round occupancy. Average water use for single-family residences with municipal water accounts in the Megansett and Squeteague Harbors MEP study area is 154 gpd. If the Megansett and Squeteague Harbors average flow is multiplied by 0.9 to account for consumptive use, the study area wastewater average flow for a single-family residence is 139 gpd.

In order to provide a check on the measured water use, the 2010 Census average occupancies were used to estimate wastewater flows. Multiplying the Census occupancies by the Massachusetts Title 5 estimate of 55 gpd of wastewater *per capita* results in an average estimated water use per residence of 138 gpd and 123 gpd for Bourne and Falmouth, respectively. Correction for minor summer occupancy increase (2X for seasonal residences) increases these estimated flows to 173 gpd and 154 gpd, respectively. This analysis suggests that population and water use information are in reasonable agreement and 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 91% of the 897 developed parcels with buildings in the Megansett and Squeteague Harbors watershed. Parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (*e.g.*, 101 or 325) and have been confirmed as having buildings on them through a review of aerial photographs, but do not have a listed account in the water use databases. Of the 85 developed parcels without water use accounts, 50 (59%) are classified as single-family residences (land use code 101). These parcels are assumed to utilize private wells and are assigned the MEP study area average water use of 154 gpd in the watershed nitrogen loading modules. Another 11 developed parcels without water use are parcels classified as other types of residential properties (*e.g.*, multi-family or condominiums). These parcels are assumed to utilize private wells. Review of multi-family water use within the MEP watershed showed that these parcels had an average water use approximately the same (153 gpd) as the single family residence average water use. For this reason, other residential parcels with private wells were assigned the study area single family residence average water use of 154 gpd. Residential units within the JBCC portion of the watershed are assumed to be connected to the JBCC sewer system; wastewater effluent from the JBCC wastewater treatment facility is discharged outside of the Megansett and Squeteague Harbors watershed.

Wastewater Treatment Facilities and Alternative Septic Systems

When developing watershed nitrogen loading information, MEP project staff typically seeks 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 systems in Falmouth and Bourne, as well as their total nitrogen effluent monitoring data, from the Barnstable County Department of Health and the Environment (personal communication, Brian Baumgaertel, 1/11). From the BCDHE database, project staff identified three denitrifying septic systems within the Megansett and Squeteague Harbors watershed. Two of the systems have three or more sampling runs that include total nitrogen effluent concentrations; the average TN concentrations for these systems are included in the watershed nitrogen loading model.

MEP staff also reviewed MassDEP Groundwater Discharge Permits (GWDPs) database and confirmed with MassDEP staff that no GWDPs were listed within the Megansett and Squeteague Harbors watershed (personal communication, Brian Dudley, MassDEP, 2/12). A GWDP is required under MassDEP regulations for wastewater treatment systems with Title 5 design flows greater than 10,000 gallons per day.

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 watershed nitrogen loading model for the Megansett and Squeteague Harbors system, MEP staff reviewed available regional information about residential lawn fertilizing practices and incorporated site-specific information for cranberry bogs and agricultural areas in the watershed. Cranberry bog nitrogen loading was determined based on previous studies conducted in southeastern Massachusetts.

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 prior to the MEP, 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. This assessment, which was completed prior to the start of the MEP, accounted for proximity to fresh ponds and embayments. Based upon ~300 interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sq. ft., 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a nitrogen leaching rate of 20% results in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors are used in the MEP nitrogen loading calculations. It is likely that this still represents a conservative estimate of nitrogen load from residential lawns. It should be noted that professionally maintained lawns in the three town survey were found to have the higher rate of fertilizer application and hence higher estimated annual contribution to groundwater of 3 lb/yr. Subsequent reviews of watershed-specific lawn sizes (Howes and White, 2005) and leaching rates (Horsley Witten Group, 2009) have generally confirmed the MEP factors as reasonable.

Fertilized areas within this watershed were all residential lawns, which were assigned nitrogen loads based on standard MEP factors. No fertilized lawn areas were assumed for non-residential land uses. There are a large number of residences within the portion of the JBCC that is within the watershed boundaries. MEP staff contacted a number of JBCC offices to try to clarify whether fertilizers are used on the lawns of these residences, but was unsuccessful in obtaining this information. For the purposes of the nitrogen loading assessment, it was assumed that lawn fertilizers were not used for these JBCC residences.

Nitrogen Loading Input Factors: Base Landfill One (LF-1)

The main former landfill on the JBCC (LF-1) is located within the upper portion of Megansett and Squeteague Harbors watershed (Figure IV-3). The landfill began use in 1941 and occupies approximately 90 acres (Jacobs Engineering, 2007). The landfill was identified as a potential source of volatile organic compounds (VOCs) in 1983 and was included in the National Priorities (Superfund) List in 1989 (USEPA, 1989). An initial characterization of the downgradient VOC groundwater plume was completed during 1992-1994 and the landfill was capped in 1995. In 1999, an extraction, treatment, and reinjection (ETR) system, including a well fence at the western JBCC boundary, was installed and began operation to begin to actively remediate VOC groundwater contamination.

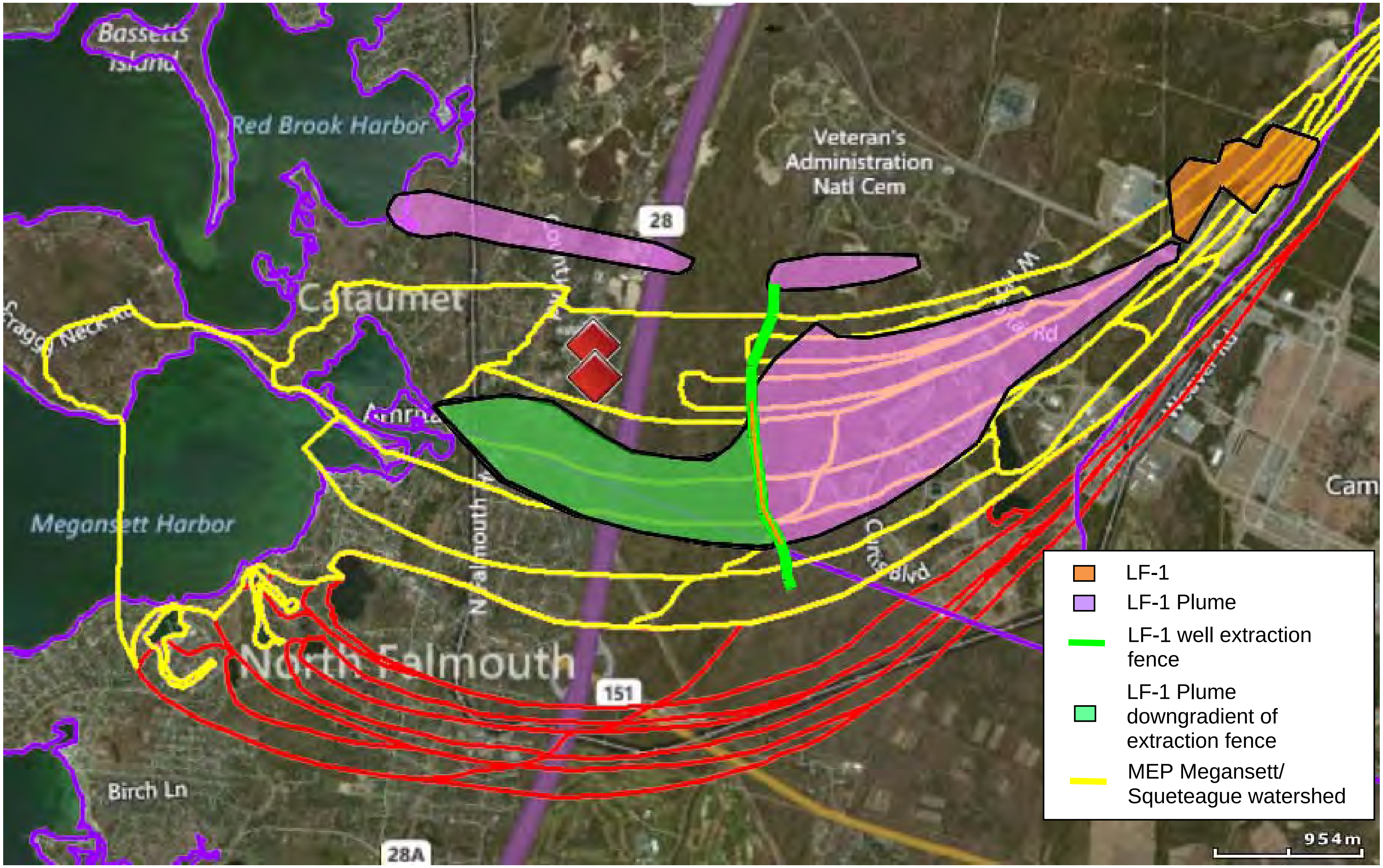


Figure IV-3. LF-1 Plume within the Megansett/Squeteague MEP watershed. The 2014 delineation of the groundwater contamination plume from the former JBCC main landfill is located mostly within the Squeteague Harbor subwatershed (IAGWSP, 2014). The plume delineation is based on chlorinated solvents greater than MCLs. The width of the plume area downgradient of the extraction fence and 1995/1996 water quality data were used to estimate a nitrogen load from the plume to Squeteague Harbor.

Characterization of the nitrogen content of the LF-1 plume has not been a primary goal of the Superfund-related investigations. However, in a previous review of nitrogen loading to Squeteague Harbor, Eichner et al. (2002) estimated an annual nitrogen load from LF-1 based on available total nitrogen concentrations at six wells downgradient of the extraction well fence measured between 1995 and 1996. Using the limited TN information, the authors used the characterization of the VOC plume, including a plume cross-section and groundwater travel time to develop annual nitrogen load of ~300 kg from LF-1 plume to Squeteague Harbor.

MEP staff reviewed 2014 characterizations of the VOC plume and sought to update the nitrogen load from the LF-1 plume. The main area of the LF-1 plume within the Squeteague Harbor subwatershed is somewhat smaller than the 2002 estimate (295 acres vs. 267 acres), but the width of the plume at the area just downgradient of the extraction well fence is longer (1670 ft vs. 3,094 ft). Since staff were unable to find/obtain updated plume TN concentrations, use of the same data with a wider cross-sectional area results in a higher 2014 annual TN load for LF-1 (713 kg/yr). This load is used in the MEP watershed nitrogen loading.

It is acknowledged that this approach for estimating a nitrogen load from the LF-1 landfill includes a number of assumptions, but it is appropriate based on the available data. A detailed assessment of all the available data is beyond the scope of the MEP, but staff balanced reasonable estimates of the various factors based on the general MEP guidance from MassDEP to include conservatism in nitrogen loading estimates when uncertainty exists in the data. A more refined evaluation and assessment of the established LF-1 monitoring well network, including, at a minimum, analysis of total nitrogen concentrations, would help to refine this assessment and future management options.

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas in the Megansett and Squeteague Harbors assessment are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the CCC's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and MassDEP's Nitrogen Loading Computer Model Guidance (1999). 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 Megansett and Squeteague Harbors watershed are summarized in Table IV-2.

Road areas are based on GIS information developed by the Massachusetts Executive Office of Transportation, which provides road, sidewalk, and road shoulder widths for various road segments. MEP staff utilized the GIS to sum these segments and their various widths by subwatershed in order to determine nitrogen loads from these impervious surfaces. Project staff also checked this information against parcel-based rights-of-way.

Building footprint data for individual parcels is based on a MassGIS Building Structures coverage that is based on digitized footprints from orthophotographs supplemented with LiDAR data. This information was used to determine roof areas which were combined other MEP nitrogen loading factors to determine nitrogen loads from these impervious surfaces.

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 subwatershed. 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 subwatershed and the sum of the area of the parcels within each subwatershed. This effort results in "parcelized" watersheds that can be more easily used during the development of management strategies.

Table IV-2. Primary Nitrogen Loading Factors used in the Megansett and Squeteague Harbors MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from town-specific or watershed-specific data.

Nitrogen Concentrations:	**mg/l**
Road Run-off	1.5
Roof Run-off	0.75
Natural Area Recharge	0.072
Direct Precipitation on Embayments and Ponds	1.09
Wastewater Coefficient	23.63
Fertilizers:	
Average Residential Lawn Size (sq ft)[1]	5,000
Residential Watershed Nitrogen Rate (lbs/lawn)[1]	1.08
Leaching rate	20%
Recharge Rates:	**in/yr**
Impervious Surfaces	40
Natural and Lawn Areas	27.25

Water Use/Wastewater:	
Existing developed single-family residential parcels wo/water accounts and buildout residential parcels:	154 gpd[2]
Existing developed parcels w/water accounts:	Measured annual water use
Commercial and Industrial Buildings without/WU and buildout additions[3]	
Commercial	
Wastewater flow (gpd/1,000 ft2 of building):	180
Building coverage:	15%
Industrial	
Wastewater flow (gpd/1,000 ft2 of building):	44
Building coverage:	5%
Average Single Family Residence Building Size within watershed (sq ft)	1,930

Notes:
1) Data from MEP lawn study in Falmouth, Mashpee & Barnstable of over 2,000 lawns (2001).
2) Based on average measured flow in the MEP watershed area
3) Based on characteristics of similarly classified properties with the Town of Falmouth

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. For example, within the town assessors' databases, the JBCC is composed of one or two large parcels and review of aerial photographs shows numerous types of buildings and various land uses; through the use of other databases, MEP staff determined impervious surfaces for each of the subwatersheds within the JBCC. Individualized information for parcels with atypical nitrogen loading (condominiums, golf courses, large parking lots, etc.) is also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the Megansett and Squeteague Harbors 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, subwatershed modules were generated for each of the 13 new subwatersheds in the Megansett and Squeteague Harbors study area. These subwatershed modules summarize, among other things: water use, parcel area, frequency, private wells, and road area. All relevant nitrogen loading data is assigned to each subwatershed. Individual sub-watershed information is then integrated to create the Megansett and Squeteague Harbors Watershed Nitrogen Loading module with summaries for each of the individual 13 subwatersheds. The results from the previously completed 20 modules to the subwatersheds to Rands Harbor and Fiddlers Cove were also incorporated (Howes et al., 2013). The subwatersheds are generally paired with functional embayment/estuary units for the Linked Watershed-Embayment Model's water quality component.

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 Megansett and Squeteague Harbors study area, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), lawn fertilizers, the JBCC landfill, 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 in streams and ponds during transport to the estuarine system before use in the embayment water quality sub-model.

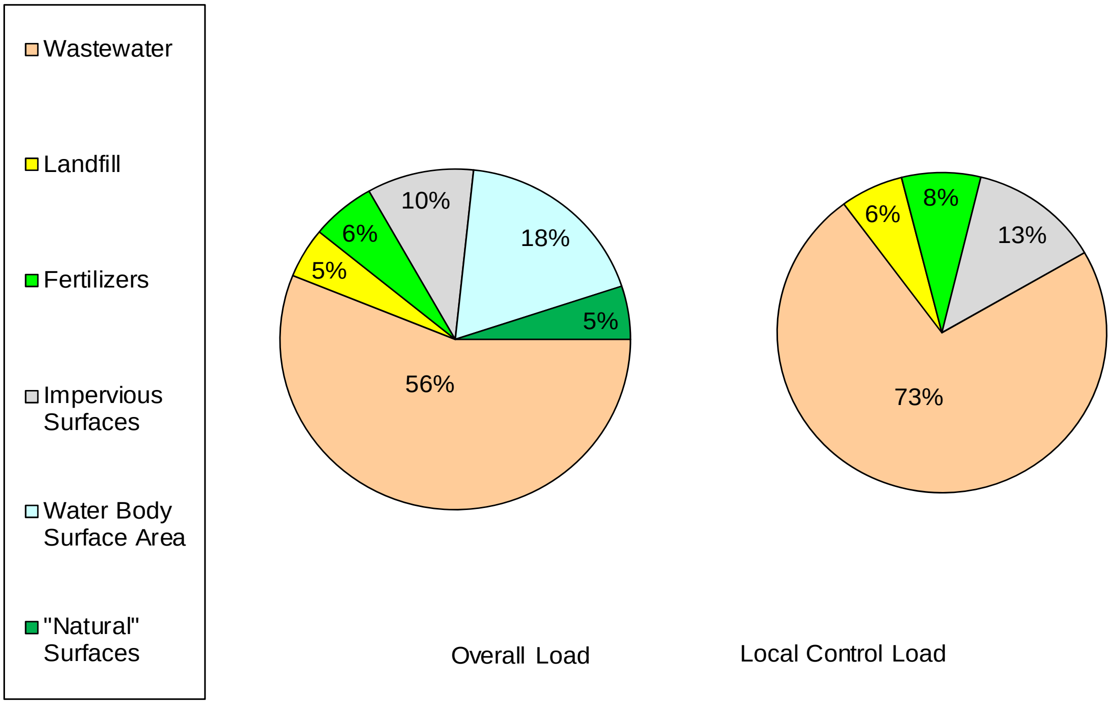
Freshwater Pond Nitrogen Loads

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 upgradient shoreline, then lake water flows back into the groundwater system along the downgradient 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 or will have their water level artificially manipulated through the use of a dam. These changes to a typical kettle hole pond configuration alter the residence time of water within the pond and can also alter the nitrogen attenuation of the pond ecosystem. 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 within the pond that returns some of the nitrogen to the atmosphere. Following these reductions, the remaining (attenuated) nitrogen loads flow back into the groundwater system along the downgradient side of the pond and eventual discharge into the downgradient embayment or through a stream outlet directly to the estuary. The nitrogen load summary in Table IV-3 includes both the unattenuated and attenuated nitrogen load to each subwatershed.

Table IV-3. Megansett and Squeteague Harbors Watershed Nitrogen Loads. Nitrogen loads are listed by various sources and by subwatershed. 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 upgradient streams and freshwater ponds. Stream attenuation factors are based on measured loads (see Section IV.2). All nitrogen loads are kg N yr^{-1}.

		Megansett/Squeteague Harbor N Loads by Input (kg/y):								Present N Loads			Buildout N Loads		
Watershed Name	Watershed ID#	Wastewater	Landfill	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout	% of Pond Outflow	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Megansett/Squeteague System		8,409	713	891	1,478	2,738	757	4,321		14,985		13,936	19,305		17,584
Squeteague Harbor Total		2,001	713	173	521	378	289	770		4,074		3,490	4,844		3,740
Squeteague Hbr GT10	2	-	-	-	77	-	22	-		99		99	99		99
Squeteague Hbr LT10	3	1,291	-	113	153	0	64	408		1,621		1,621	2,028		2,028
Megansett Road Gauge Total		442	713	40	144	-	83	230		1,421	40%	853	939	40%	563
Osborne Pond	OP	-	-	-	12	13	7	-	34%	31	50%	16	31	50%	16
Olofson Rd	1	268	-	21	95	0	80	132		464		464	596		596
BWD_Well N	12	-	-	-	22	-	13	-		35		35	35		35
BWD_Well S	13	-	-	-	19	-	20	-		39		39	39		39
Squeteague Hbr Estuary Surface						365				365		365	365	-	365
Megansett Channel Total		1,009	-	96	172	158	77	311		1,512		1,491	1,823		1,802
Megansett Channel GT10	8	-	-	-	35	-	26	-		61		61	61		61
Megansett Channel LT10	9	1,009	-	96	121	-	42	311		1,268		1,268	1,579		1,579
Osborne Pond	OP	-	-	-	16	17	9	-	46%	42	50%	21	42	50%	21
Megansett Channel Estuary Surface						141				141		141	141	-	141
Megansett Harbor Total		5,398	-	621	785	2,202	392	3,240		9,398		8,955	12,639		12,042
Megansett Hbr GT10	10	-	-	-	66	-	78	333		144		144	477		477
Megansett Hbr LT10	11	2,011	-	157	173	-	48	173		2,389		2,389	2,562		2,562
Osborne Pond	OP	-	-	-	7	8	4	-	20%	19	50%	9	19	50%	9
Cedar Lake	CL	520	-	33	95	61	46	254	46%	755	20%	587	1,009	20%	791
Rands Harbor System	TOTALS	1,652	-	172	363	153	178	2,066		2,519		2,269	4,585		4,233
Fiddlers Cove System	TOTALS	1,215	-	259	81	71	37	413		1,664		1,648	2,077		2,060
Megansett Hbr Estuary Surface						1,909				1,909		1,909	1,909	-	1,909

		Stream and Pond N Loads by Input (kg/y)								Present N Loads			Buildout N Loads		
Watershed Name	Watershed ID#	Wastewater	Landfill	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout	% of Pond Outflow	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
streams															
Megansett Road Gauge Total		442	713	40	144	-	83	230		1,421	40%	853	1,651	40%	563
Squeteague Stream GT10	4	-	-	-	81	-	39	-		121		121	121		121
Squeteague Stream LT10	5	442	713	40	62	-	44	230		1,300		1,300	818		818
ponds															
Osborne Pond Total	OP	-	-	-	34	37	20	-		92	50%	46	92	50%	46
Osborne Pond GT10	6	-	-	-	4	-	5	-		8		8	8		8
Osborne Pond LT10	7	-	-	-	30	37	16	-		84		84	84		84
Cedar Lake Total	CL	1,120	-	71	205	132	99	548		1,627	20%	1,266	2,175	20%	1,704

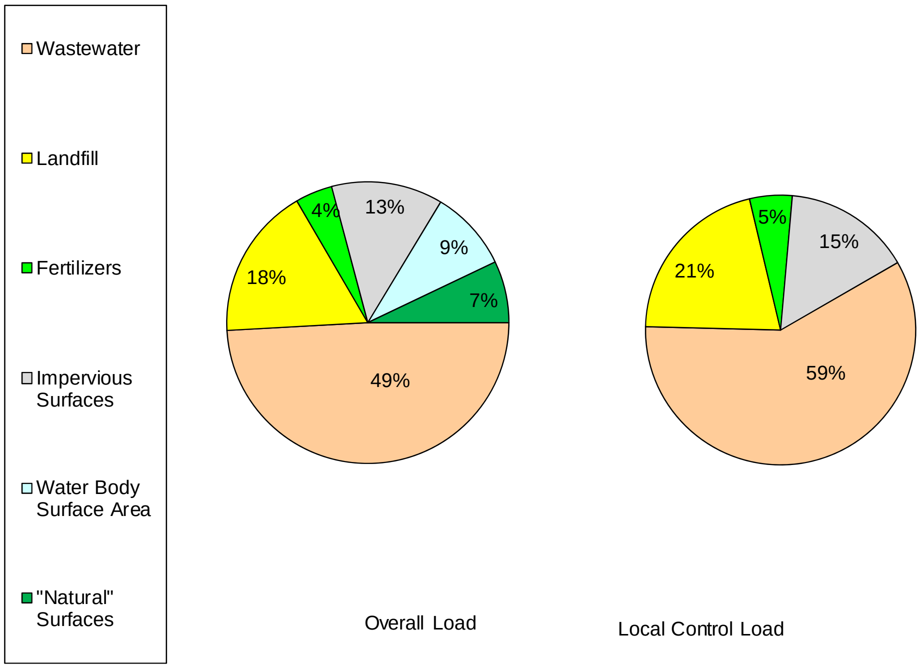


a. Megansett/Squeteague System Total

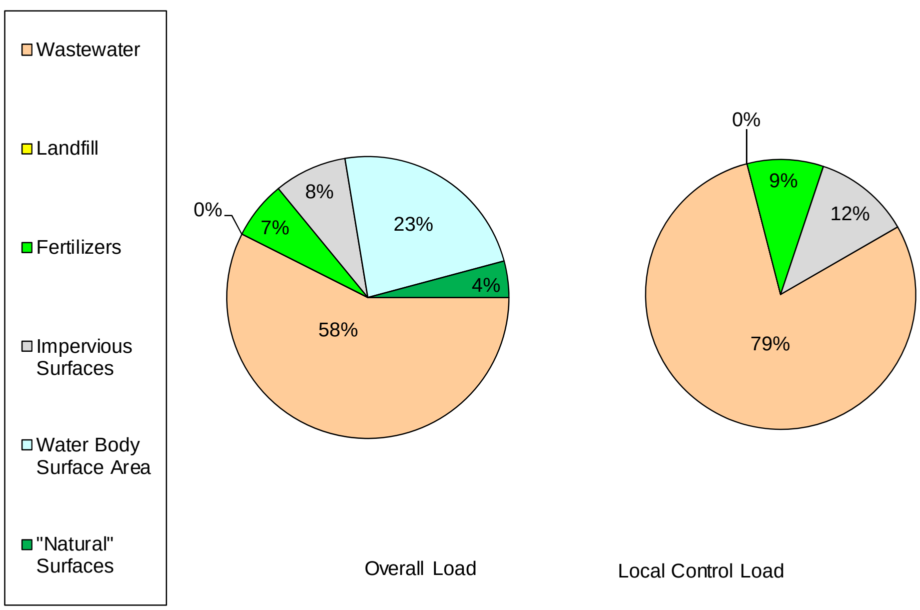
Figure IV-4 (A). Source-specific unattenuated watershed nitrogen loads (by percent) to the A) whole Megansett and Squeteague Harbors watershed. “Overall Load” is the total nitrogen input within the watershed, while the “Local Control Load” represents only those nitrogen sources that could potentially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

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, 2000) 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 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 nitrogen attenuation.



b. Squeteague Harbor Total



c. Megansett Harbor Total

Figure IV-4 (B,C). Source-specific unattenuated watershed nitrogen loads (by percent) to the B) Squeteague Harbor subwatershed and C) Megansett Harbor subwatershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.

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 warm isothermic, 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 location in the pond for watershed nitrogen loads; the deeper hypolimnion generally has limited interaction with the upper layer during stratification. However, impaired conditions in a deeper hypolimnion can result in significant sediment regeneration of nitrogen. In these lakes/ponds, regenerated sediment nitrogen can filter into the upper layer and impact measured nitrogen concentrations. For this reason, water quality conditions in the ponds should also be considered when estimating nitrogen attenuation, if appropriate data is available.

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 Cape Cod PALS Snapshots are regional volunteer, late-summer pond sampling supported for the last fourteen 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 Cape Cod 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 of standardized depths that include some evaluation of the impact of sediment nutrient regeneration. Cape Cod 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 collected throughout a number of summers that modified MEP nitrogen attenuation rates can be reliably assigned to freshwater ponds.

Within the Megansett and Squeteague Harbors study area, there are two freshwater ponds with delineated watersheds: Osborne Pond and Cedar Lake. Neither pond has available pond-wide bathymetric data (Eichner et al., 2003) or sufficient water quality data collection outside of the MEP to provide a basis for an alternative nitrogen attenuation rate. Osborne Pond has been evaluated for Superfund-related contamination, but that evaluation did not include monitoring for nitrogen or bathymetry (ECC, 2013). Cedar Lake has been sampled six times during the nine years of Cape Cod Pond and Lakes Stewardship (PALS) Snapshots and Osborne Pond has not been sampled through the PALS Program.

Although neither of the freshwater ponds has sufficient in-pond sampling or adequate bathymetry to assign an alternative MEP nitrogen attenuation rate, MEP staff did have a stream gauge at the Cedar Lake surface water outlet to help to evaluate its water and nitrogen flow. This monitoring was documented in the Fiddlers Cove and Rands Harbor MEP report (Howes et al., 2013). Using the information collected at this gauge, MEP staff assigned a 20% nitrogen attenuation rate to Cedar Lake. This attenuation rate balanced the measured flow and load leaving the pond through the stream gauge and indicated discharge of a portion of the watershed flow and load from the pond through its downgradient shoreline. The portion of the flow leaving through the Cedar Lake downgradient shoreline discharges into the Megansett Harbor subwatershed. Osborne Pond, on the other hand, did not have any detailed information and was assigned the MEP standard 50% nitrogen attenuation rate for freshwater ponds. More refined evaluation of these ponds would offer the opportunity to refine these attenuation rates and evaluation of management options to increase the attenuation rates and naturally remove additional nitrogen.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment (or scenario) of potential development and accompanying nitrogen loads within the study area watershed. 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 undeveloped areas greater than twice zoning's minimum lot size are identified, divided by the minimum lot size and the resulting number of new units is rounded down, and 4) results are discussed with town staff and/or planning board members and the analysis results are modified based on local knowledge.
It should be noted that the initial MEP buildout approach is relatively simple and does not initially include any modifications/refinements for more detailed zoning provisions, such as lot line setbacks, wetlands, road construction, frontage requirements, and parcel shape requirements. 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 (MassDOR 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 subwatershed in the MEP buildout scenario. This addition could then be modified during discussion of town staff.

Other provisions of the MEP buildout assessment include town assessor classification of undevelopable lots, standard treatment of commercial and industrial properties, and assumptions for lots less than the minimum areas specified by zoning. Undeveloped properties classified by the town 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 an estimated building size and wastewater flow for these properties. Pre-existing lots smaller than zoning minimum lot sizes, but classified by the town assessor as developable are also treated as developable; so, for example, a 10,000 square foot lot classified by the town assessor as a developable residential property (MassDOR 130 land use code) and located in a zoning area with a 40,000 square feet minimum lot size will be assigned an additional residential dwelling in the MEP buildout scenario. 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 lot size minimum.

Following the completion of the initial buildout assessment for the Megansett and Squeteague Harbors watersheds, MEP staff reviewed the results with Bourne town officials.

MEP staff reviewed the preliminary watershed buildout results with Coreen Moore, Bourne Town Planner in January 2015. MEP staff made numerous attempts to have a similar review by Town of Falmouth staff, but was unsuccessful. All suggested changes to the initial buildout results from Bourne staff were incorporated into the final MEP buildout for Megansett and Squeteague Harbors.

All the parcels with additional buildout potential within the Megansett and Squeteague Harbors watershed are shown in Figure IV-5. 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. Cumulative unattenuated buildout loads are indicated in a separate column in Table IV-3. It should be noted that this is one example of a buildout scenario; alternative assumptions about future development could be developed to assess the water quality impacts of other buildout scenarios. Based on the MEP assessment, buildout additions within the Megansett and Squeteague Harbors watersheds will increase the unattenuated watershed nitrogen loading rate by 29%.

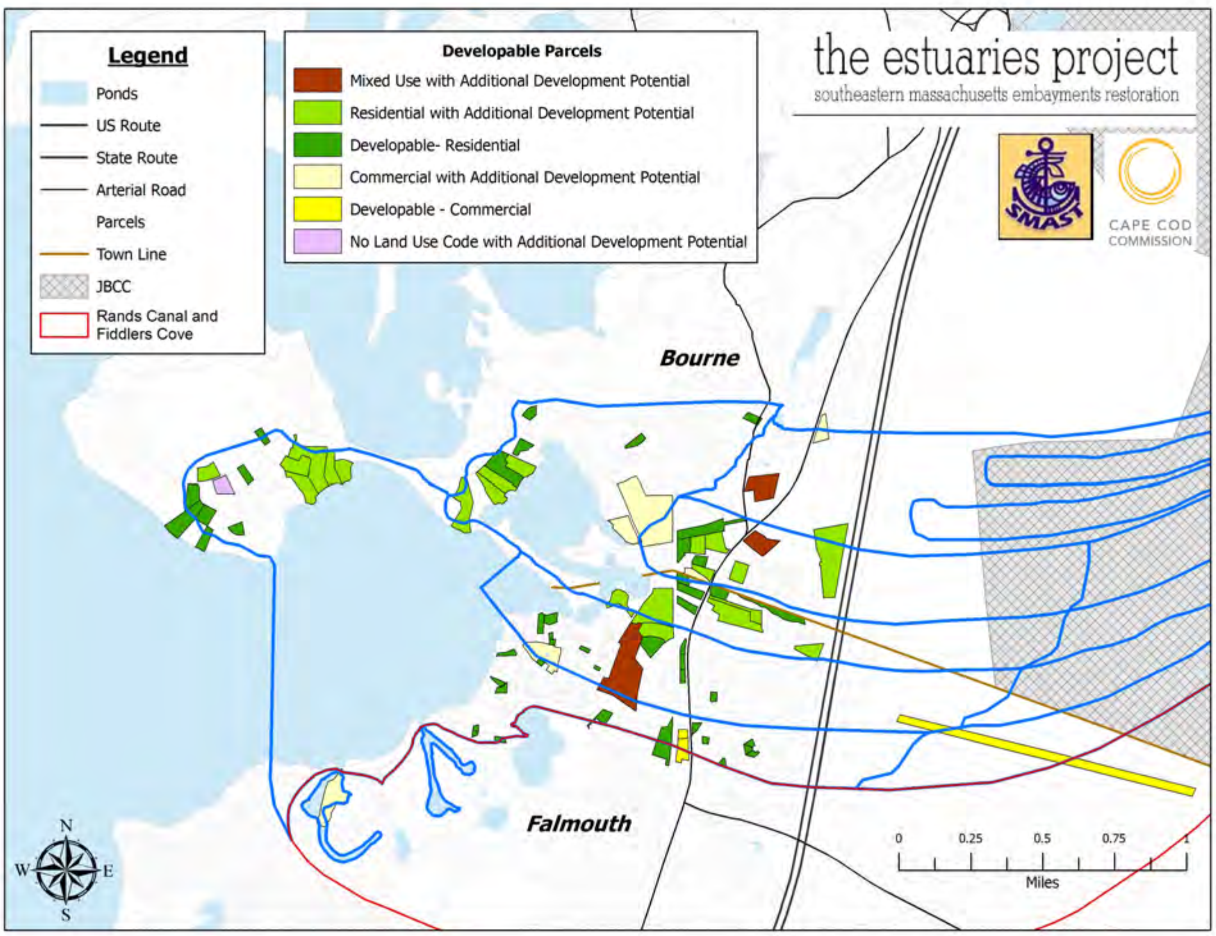


Figure IV-5. Developable Parcels in the Megansett and Squeteague Harbors watershed.

Parcels colored light green, red, light yellow, and light purple are developed parcels (residential, mixed use, commercial and no land use code, respectively) with additional development potential based on current zoning, while parcel colored dark green and yellow are corresponding undeveloped residential and commercial parcels, respectively, classified as developable by the town assessor. Parcels along watershed boundaries are assigned to subwatersheds to 1) minimize the splitting of properties for future management purposes and 2) achieve a match of area with the modeled watersheds of 2% or less. Developable parcels are based on town assessor classifications and minimum lot sizes specified in current town zoning; these parcels are assigned estimated nitrogen loads in MEP buildout calculations. Initial MEP buildout results within the Town of Bourne were reviewed with town officials and any corrections were incorporated into the final buildout nitrogen loads. The eastern portions of the watershed are all within JBCC and are all one parcel; no additional development was assumed for this portion of the JBCC.

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 Megansett Harbor and Squeteague 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 Megansett Harbor and Squeteague Harbor watershed). 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 Squeteague Harbor portion of the overall embayment system, a fraction of the freshwater flow and transported nitrogen passes through a surface water system (Squeteague Stream discharging from Cuffs Pond) prior to entering the estuary, producing the opportunity for reductions in nutrient loading, primarily through nitrogen attenuation (Figure IV-6). There are no significant surface water discharges (creeks, streams, rivers) associated with Megansett Harbor directly. Some fresh surface water flow does, however, make it to the Megansett Harbor basin but only after first discharging to Rands Harbor. Nitrogen attenuation in ponds within the watershed to Squeteague Harbor (also the case for Rands Harbor watershed) was taken into consideration in the analysis of nitrogen loading from the watershed based on land use.

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 2000). 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.

Figure IV-6. Location of Squeteague Stream flow gauge and nitrogen load measurements (red symbol) associated with the Squeteague Harbor Embayment System.

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 Squeteague Harbor portion of the overall 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 single major surface water flow system in the Squeteague Harbor watershed, Squeteague Stream discharging from Cuffs Pond.

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 gauging site. Flow and nitrogen load were determined at one gauge location for 16 months of record (Figures IV-6 and IV-7). During the study period, a velocity profile was completed at the gauge positioned in the stream 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) through a given stream.

Determination of flow at the gauge on Squeteague Stream discharging to Squeteague Harbor was calculated and based on the measured values obtained for cross sectional area of the stream as well as measured velocity. Freshwater discharge was represented by the summation of individual discharge calculations for the 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, rather flow through individual sub-sections were determined and summed to determine the discharge through the entire stream cross-section.

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 has a calculated stream discharge value and the summation of all the sub-sectional stream discharge values becomes 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 was 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 stream. 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 streams (365 days) was generated for the surface water discharge flowing into the Squeteague Harbor portion of the embayment system and emanating from Cuffs Pond.

Annual flow record for the surface water flow at the gauge was merged with the nutrient data set generated through weekly water quality sampling performed at the gauge location to determine nitrogen loading rates to the harbor basin. Nitrogen discharge from the small stream was calculated using paired daily discharge and daily nitrogen concentration data to determine the mass flux of nitrogen through the specific gauging site. For the stream gauge location, weekly water samples were collected (at low tide for a tidally influenced stage) in order to determine nutrient concentrations from which nutrient load was calculated. 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 measured nitrogen loads based on flow in the stream and water quality sampling to predicted loads based on the land use analysis allowed for determination of the degree to which natural biological processes within the watershed to the gauged stream currently reduces (percent attenuation) nitrogen loading to the overall embayment system.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Squeteague Stream flowing into Squeteague Harbor from Cuffs Pond

Located up-gradient of the stream gauge on Squeteague Stream discharging into the estuarine basin of Squeteague Harbor is a small freshwater pond, Cuffs Pond. Cuffs Pond, unlike many of the freshwater ponds on Cape Cod, has a surface water discharge rather than draining solely to the aquifer along its down-gradient shore. This outflow through Squeteague Stream may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of nitrogen load from the sub-watershed and the extent of nitrogen attenuation. In addition, nitrogen attenuation occurs within associated wetland areas, riparian zones and streambed associated with the Stream. 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 stream gauge and the measured annual discharge of nitrogen to the tidal reaches of the Squeteague Harbor basin.

At the Stream gauge site (situated immediately up-gradient of Megansett Road, Figure IV-6), a continuously recording vented calibrated water level gauge was installed to yield the level of water in the freshwater stream discharging from Cuffs Pond and which carries the flows and associated nitrogen load to Squeteague Harbor portion of the overall embayment system. As the culvert passing under Megansett Road is tidally influenced, the gauge was located as far down gradient along the Stream reach such that freshwater flow could be measured at low tide. To confirm the lack of tidal influence as observed in the stage record, salinity measurements were 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. Therefore, 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 for a flow measurement. The gauge on the Stream was installed on June 22, 2005 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 October 30, 2006 for a total deployment of 16 months.

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for Squeteague Stream 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 estuarine portion of inner Squeteague Harbor. This measured attenuated mass discharge is reflective of the biological processes occurring in Cuffs Pond as well as the stream channel and riparian zone contributing to nitrogen attenuation (Figure IV-7 and Table IV-4,5). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at the gauge site.

The annual freshwater flow record for the Stream flowing under Megansett Road and into Squeteague Harbor 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 only 6% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for one hydrologic year beginning September and ending in August (low flow to low flow) was 3,302 m^3/day compared to the long term average flows determined by the USGS modeling effort (3,493 m^3/day).

The difference between the long-term average flow based on hydrologic balance (recharge rates and watershed area) and the MEP measured flow in 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 Cuffs Pond would indicate that the Stream is capturing the up-gradient recharge (and loads) accurately and that the model is accurately delineating the watershed areas.

Total nitrogen concentrations within the Stream outflow were moderate, 0.699 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 2.31 kg/day and a measured total annual TN load of 843 kg/yr. In the Stream (freshwater), nitrate was approximately half (48%) of the measured total nitrogen concentration, indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was only partially taken up by plants within the small up-gradient pond (Cuffs Pond) or stream ecosystem, as seen in the dissolved and particulate organic nitrogen levels. The nitrate level (0.336 mg N L^{-1}) in the out-flowing stream water suggests the possibility for some additional uptake by freshwater systems up-gradient from the gauge location. Inorganic nitrogen (DIN), which represents 49% of the TN load being discharged to the estuary, could potentially be further attenuated through the enhancement of natural attenuation upgradient of the gauge (e.g. restoration of Cuffs Pond) or riparian wetlands. Opportunities for enhancing nitrogen attenuation elsewhere in the overall sub-watershed to Squeteague Harbor could be considered, as there is likely to be additional natural attenuation to be gained from the Stream-Cuffs Pond sub-watersheds.

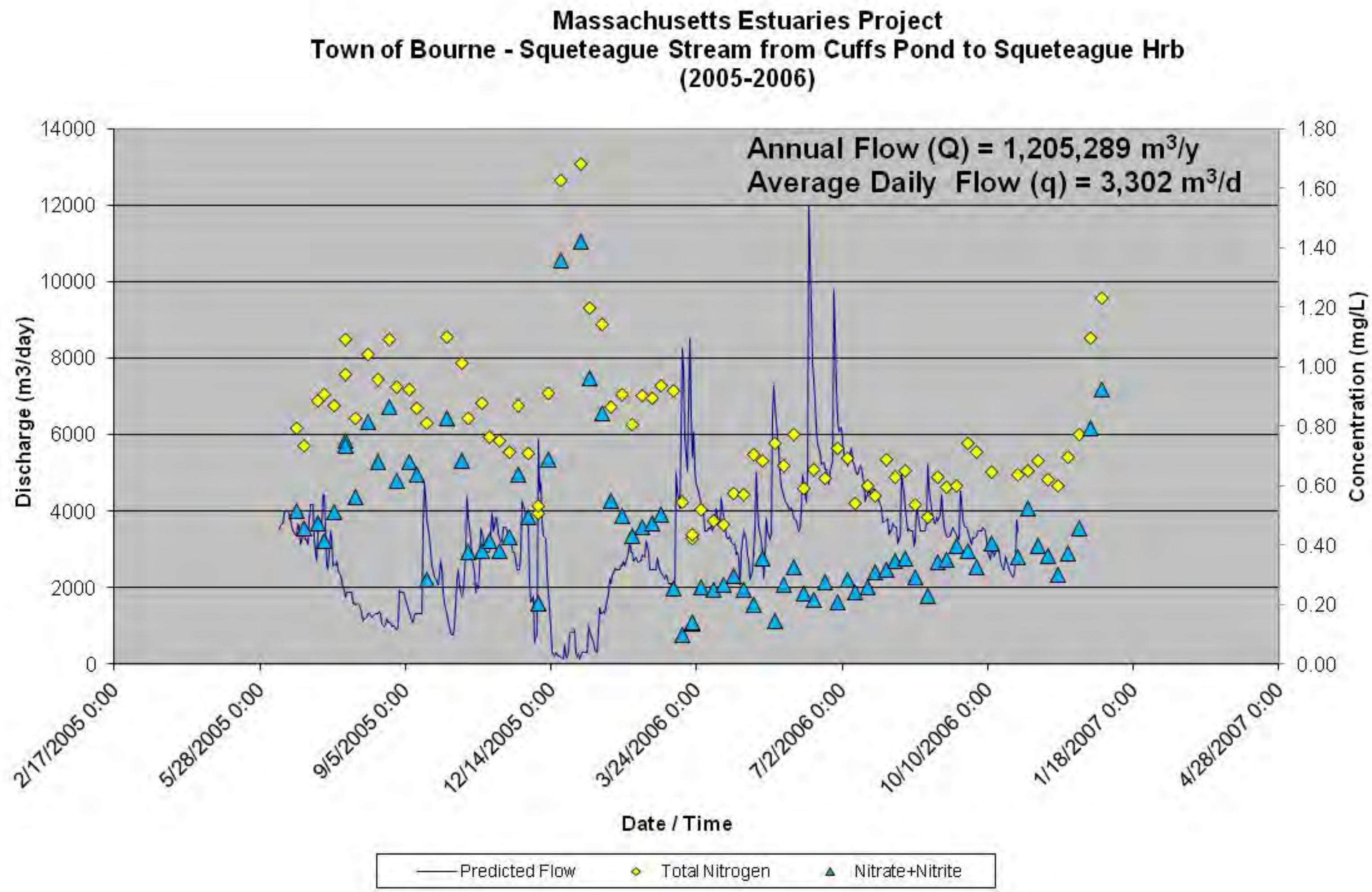


Figure IV-7. Squeteague Stream flowing under Megansett Road and discharging directly into Squeteague Harbor (solid blue line), nitrate+nitrite (blue symbol) and total nitrogen (yellow symbol) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Megansett Harbor and Squeteague Harbor (Table IV-4).

Table IV-4. Comparison of water flow and nitrogen discharges from Squeteague Stream (freshwater) discharging to Squeteague Harbor from Cuffs Pond. The "Stream" data is from the MEP stream gaging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	**Cuffs Pond Discharge**[a] (Squeteague Hrb)	**Data Source**
Total Days of Record	365[b]	(1)
Flow Characteristics		
Stream Average Discharge (m3/day) **	3,302	(1)
Contributing Area Average Discharge (m3/day)	3,493	(2)
Discharge Stream 2005-06 vs. Long-term Discharge	6%	
Nitrogen Characteristics		
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.336	(1)
Stream Average Total N Concentration (mg N/L)	0.699	(1)
Nitrate + Nitrite as Percent of Total N (%)	48%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	2.31	(1)
TN Average Contributing UN-attenuated Load (kg/day)	3.89	(3)
Attenuation of Nitrogen in Pond/Stream (%)	40.6%	(4)

(a) Flow and N load to stream discharging to Squeteague Harbor and includes apportionments of Pond contributing areas.
(b) September 1, 2005 to August 31, 2006.

** Flow is an average of annual flow for 2005-2006

(1) MEP gage site data
(2) Calculated from MEP watershed delineations to ponds upgradient of specific gauge; the fractional flow path from each sub-watershed which contribute to the flow in the stream to Squeteague 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 stream vs. the unattenuated watershed load.

Table IV-5. Summary of annual volumetric discharge and nitrogen load from the un-named stream discharging to Squeteague Harbor from Cuffs Pond. Flows and loads based upon the data presented in Figure IV-7 and Table IV-4. The moderate nitrate+nitrite (Nox) load reaching the estuary suggests that enhanced attenuation may be possible in this system.

Embayment System	Period of Record	Discharge (m^3/yr)	Attenuated Load (kg/yr)	
			Nox	TN
Squeteague Harbor Stream discharge from Cuffs Pond (MEP)	September 1, 2005 to August 31, 2006	1,205,289	405	843
Squeteague Harbor Stream discharge from Cuffs Pond (CCC)	Based on Watershed Area and Recharge	1,274,945	-	-

From the measured nitrogen load discharged by the Stream to the harbor basin and the nitrogen load determined from the watershed based land use analysis, it appears that nitrogen attenuation is occurring during transport of upper watershed derived nitrogen during transport to the estuary. Based upon lower total nitrogen load (843 kg yr^{-1}) discharged from the freshwater Stream compared to that added by the various land-uses to the associated watershed (1,421 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is ~40% (i.e. 40% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other small ponds with outlet streams evaluated under the MEP is expected given the hydrologic and biogeochemical characteristics of the up-gradient pond(s) capable of attenuating nitrogen. The directly measured nitrogen loads and attenuation rate from the Stream were used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

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

IV.3.1 Sediment-Water column Exchange of Nitrogen

As stated in the above section, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the Megansett/Squeteague Harbor Estuarine System predominantly in highly bio-available forms from the surrounding upland watersheds and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered), then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bio-available form nitrate. This nitrate and other bio-available forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton "particles". Most of these "particles" remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like Buzzards Bay). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with an associated nitrogen "load" becomes 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 both Megansett Harbor and Squeteague Harbor. 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 Megansett and Squeteague 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 throughout the basins in both 2005 and 2014 in July-August. Samples were collected in the Megansett Harbor basin at 8 locations in both years, in Megansett channel (Jetty to inlet to

Squeteague) 6 locations sampled in 2005 (3 of which were sampled again in 2014), Squeteague Harbor 6 locations in both years (Figures IV-8 and IV-9). The areal distribution of flux measurements was selected to be representative of nutrient fluxes throughout the system inclusive of tributary "basins" such as the narrow channel that extends landward off the main embayment basin. Duplicate cores were taken at one site. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. 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 Figures IV-8 and IV-9. Sampling was distributed throughout the estuary such that the results for each site could be combined to calculate the net nitrogen regeneration rates for the water quality modeling effort.

Megansett Harbor Benthic Nutrient Regeneration Cores (2005 and 2014)

- MG-1 1 core (Outer Basin, 2005+2014)
- MG-2 1 core (Outer Basin, 2005+2014)
- MG-3 1 core (Outer Basin, 2005+2014)
- MG-4 1 core (Outer Basin, 2005+2014)
- MG-5 1 core (Outer Basin, 2005+2014)
- MG-6 1 core (Outer Basin, 2005+2014)
- MG-7 1 core (Outer Basin, 2005+2014)
- MG-8 1 core (Outer Basin, 2005+2014)
- MG-9 1 core (Megansett Channel, 2005+2014)
- MG-10 1 core (Megansett Channel, 2005+2014)
- MG-11 1 core (Megansett Channel, 2005)
- MG-12 1 core (Megansett Channel, 2005)
- MG-13 1 core (Megansett Channel, 2005+2014)
- MG-16 1 core (Megansett Channel, 2005)

Squeteague Harbor System Benthic Nutrient Regeneration Cores (2005 and 2014)

- MG-14 1 core (Main Basin, 2005+2014)
- MG-15 1 core (Main Basin, 2005+2014)
- MG-17 1 core (Main Basin, 2005+2014)
- MG-18 1 core (Main Basin, 2005+2014)
- MG-19 1 core (Main Basin, 2005+2014)
- MG-20 1 core (Main Basin, 2005+2014)

Sediment-water column exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes (1998) for nutrients and metabolism. Upon return to the field laboratory (Megansett Harbor Yacht Club), 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.

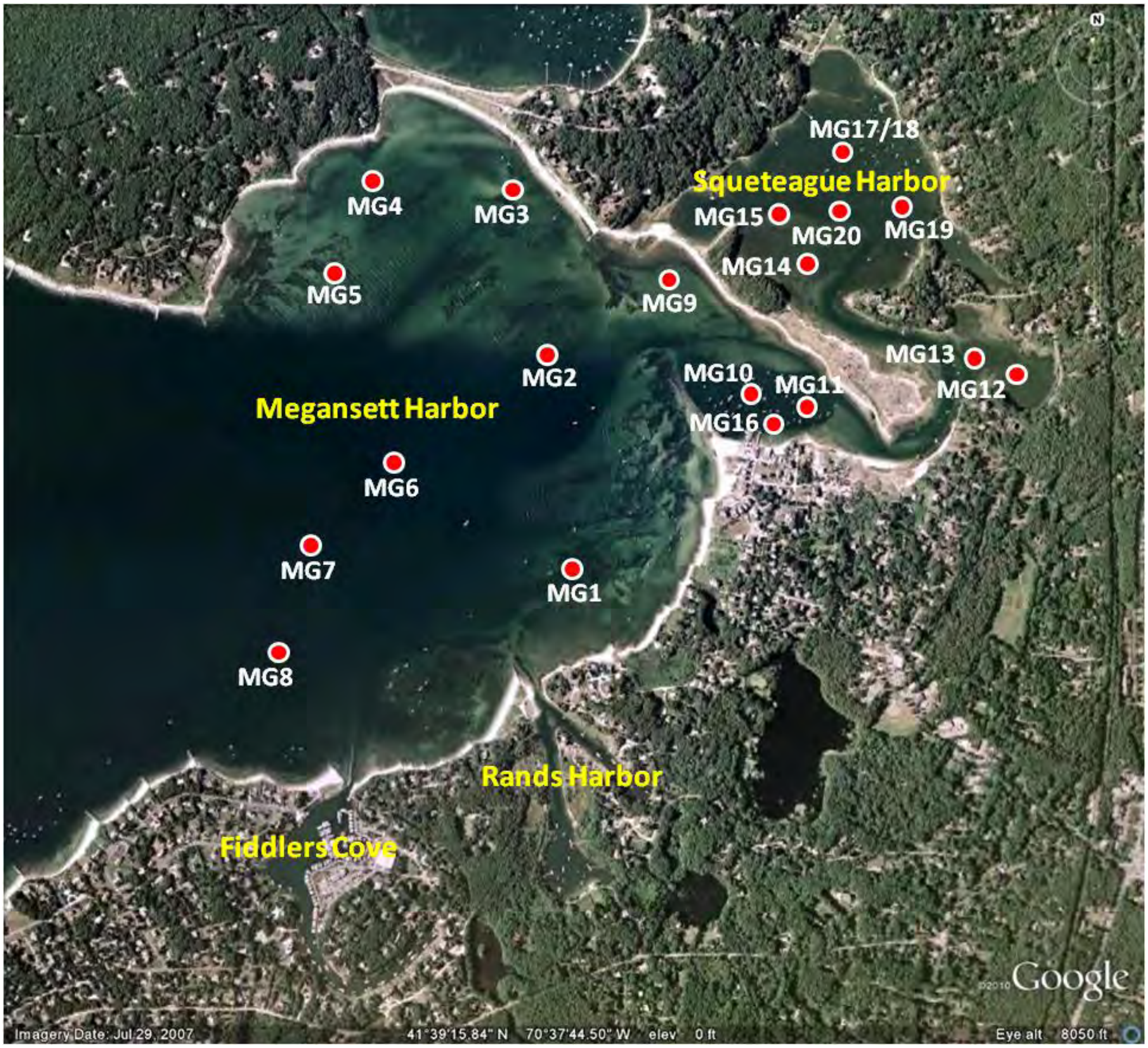


Figure IV-8. Megansett / Squeteague Harbor embayment system locations (red symbols) of sediment sample collection for determination of nitrogen regeneration rates (summer 2005 survey). Numbers are for reference in Table IV-6.

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.

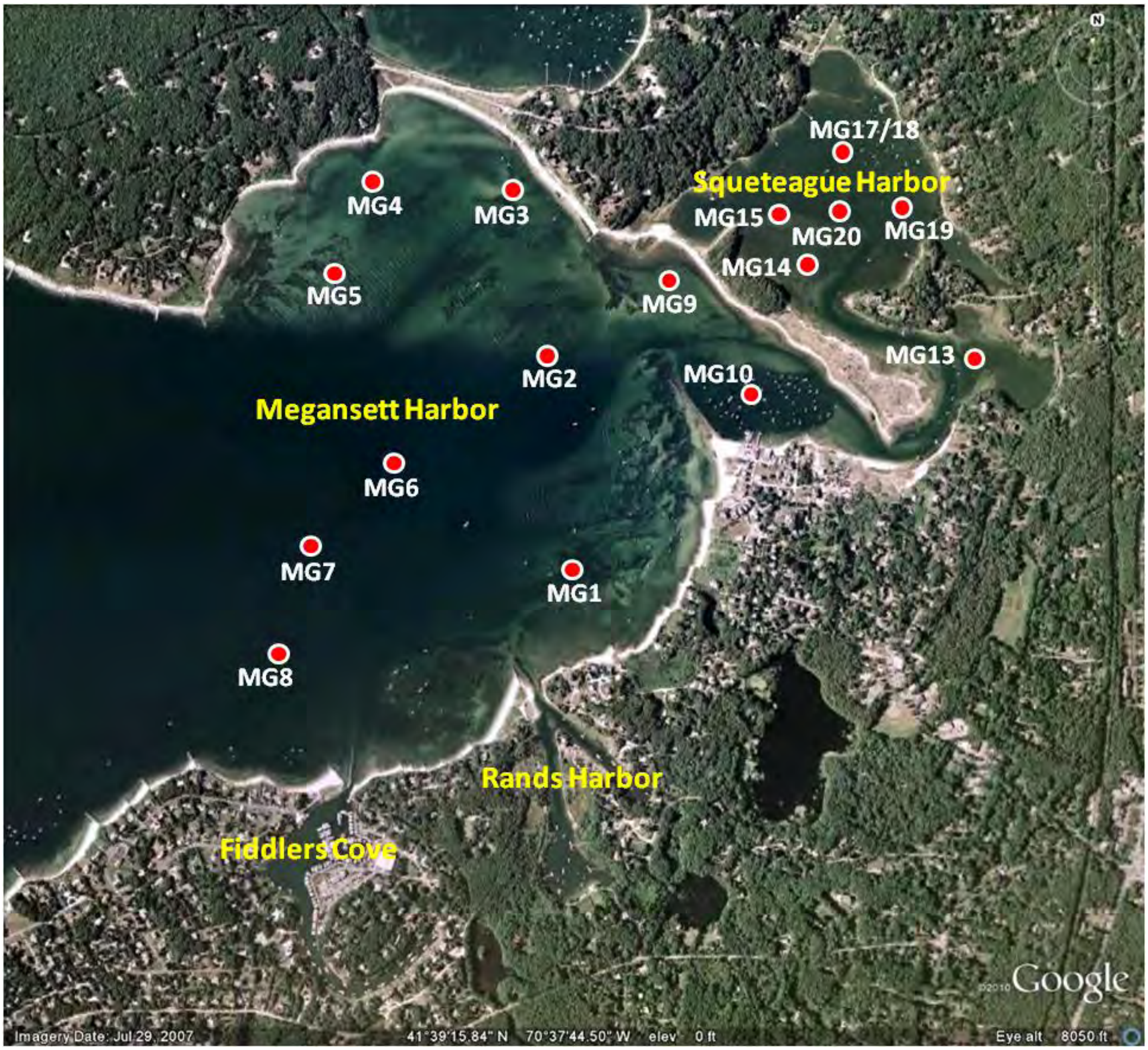


Figure IV-9. Megansett / Squeteague Harbor embayment system locations (red symbols) of sediment sample collection for determination of nitrogen regeneration rates (summer 2014 survey). Numbers are for reference in Table IV-6.

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 a 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-10).

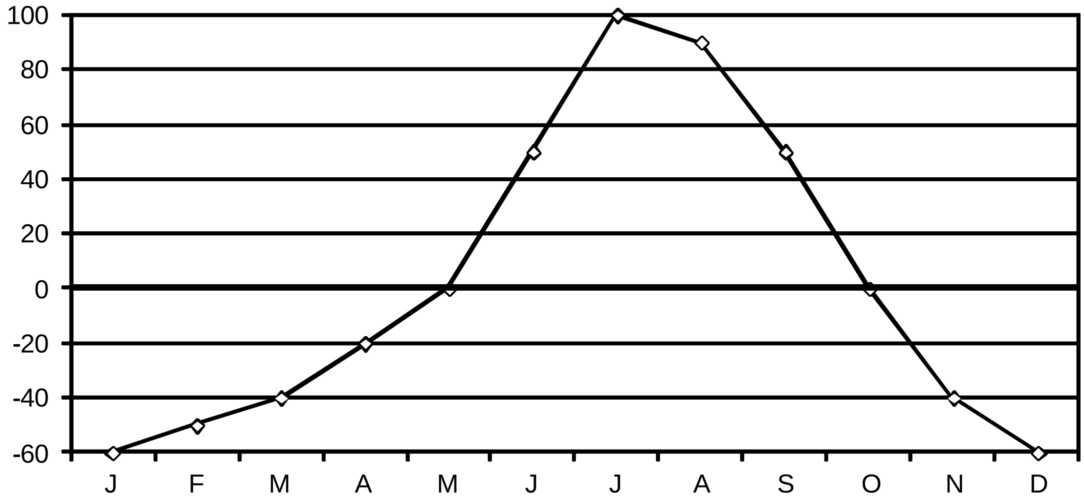


Figure IV-10. Conceptual diagram showing the seasonal variation in sediment N flux (y-axis), with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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 basins of each of the two harbors in both the summer of 2005 and the summer of 2014. In Megansett Harbor, samples were collected in the outer more exposed portion of the main basin as well as inside the rock jetty that creates an inner protected area that constitutes the yacht club marina area. In the Squeteague Harbor portion of the overall system, samples were collected from both the inner most basin that constitutes the harbor as well as from the channel that connects Squeteague Harbor to Megansett Harbor. 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 both the inner most portions of the harbor system with the exception of the channel area in the immediate vicinity of the tidal inlet. 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 (Section V). Based upon the moderate to low velocities, a water column particle residence time of ~4-8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins). Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas that are net nitrogen sinks for the aquatic system. This approach has been previously validated in outer Cape Cod embayments (Town of Chatham) by examining the relative fraction of the sediment carbon turnover (total sediment metabolism) which would be accounted for by daily particulate carbon settling. This analysis indicated that generally 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 Megansett/Squeteague Harbor Estuarine System were comparable to other embayments of similar depth and configuration in southeastern Massachusetts. There was a clear pattern of sediment N flux. The inner basin appears to be depositional, but with oxidized fine grained sediments. The outer basin is less isolated with a deeper central section (~5 m) with extensive shallow margins supporting eelgrass (see bathymetric map, Section V). Consistent with the morphology of the basins, the inner basin sediments consist mainly of fine sands and muds, while the outer basin sediments are mainly coarse to fine sands. Sediments at all sites exhibited an oxidized surface layer and were "non-sulfidic". Summertime nitrogen exchange between sediments and overlying water indicated that the inner basin sediments were a net source of nitrogen to the waters (5.8 mg N m^{-2} d^{-1}), while the outer basin sediments showed net uptake (-4.8 mg N m^{-2} d^{-1}; Table IV-6). The spatial pattern of sediment-watercolumn exchange is consistent with basin morphology, sediment type and water depth. The difference in sediment nitrogen flux may also be correlated with the occurrence of eelgrass beds throughout the outer basin, with no discernible patches in the inner basin.

The rates of net nitrogen release or uptake from the sediments within the Megansett Harbor and Squeteague Harbor Estuarine System generally showed a gradient in rates being highest in the enclosed basin of Squeteague Harbor, intermediate in the channel to Megansett Harbor and lowest in the open main basin of Megansett Harbor. This pattern in rates parallels the phytoplankton biomass (chlorophyll a pigments) in the overlying waters and the variation in tidal flushing between the basins. The spatial pattern of sediment-water column exchange is also consistent with basin morphology and sediment type, as indicated above. Similarly the net nitrogen release rates throughout the Megansett/Squeteague estuarine basins were comparable to other embayments of similar depth and configuration in southeastern Massachusetts. Similar Buzzards Bay embayments showed similar rates and spatial patterns. Nasketucket Bay has a semi-enclosed inner basin and open water outer basin with a similar gradient in rates from 13.7-10.2 mg N m^{-2} d^{-1} (inner) and -8.5 mg N m^{-2} d^{-1} (outer), while similarly configured nearby Phinneys Harbor Estuary has rates of 9.4 mg N m^{-2} d^{-1} (inner) declining to 2.9 mg N m^{-2} d^{-1} (outer basin). Finally, a similarly nitrogen enriched estuary with inner enclosed and outer open basins, Quissett Harbor also was found to have a comparable spatial patter in rates, with the outer basin having generally oxidized sandy to sand/mud (mix) sediments and showing net uptake, -12.2 mg N m^{-2} d^{-1}, while the more depositional and organic sediments of the inner basin supporting a moderate level of net nitrogen release, 32.0 mg N m^{-2} d^{-1}. The magnitude of the sediment nitrogen release/uptake rates within these estuaries reflect the phytoplankton biomass in the watercolumn during summer, while the spatial pattern is determined by tidal flushing, sediment type and basin morphology.

Overall, the summer nitrogen release from the sediments within the component basins of the Megansett Harbor and Squeteague Harbor Estuarine System is 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 (Section VI) are presented in Table IV-6.

Table IV-6. Rates of net nitrogen return from sediments to the overlying waters of the Megansett/Squeteague Harbor Estuary. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Section VI). Measurements represent average July - August rates from 2005 and 2014 surveys.

	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			
Location	**Mean**	**S.E.**	**N**	**i.d. ***
Megansett Harbor				
Outer Basin	**- 4.8**	**1.7**	**16**	MG- 1,2,3,4,5,6,7,8
Inner Basin and Channel	**0.4**	**14.0**	**8**	MG- 9,10,11,12,13,16
Squeteague Harbor				
Main Basin	**5.8**	**4.8**	**12**	MG-14,15,17,18,19,20

* Station numbers refer to Figures IV-8 and 9.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This hydrodynamic study was performed for Megansett Harbor, located at the border between Falmouth and Bourne, Massachusetts, on the eastern shoreline of Buzzards Bay. It is the receiving basin of groundwater flow from the Megansett area of North Falmouth and portions of the village of Cataumet in Bourne. A topographic map detail in Figure V-1 shows the general study area. The main basin of Megansett Harbor is moderately deep coastal embayment with a wide opening to the Bay that is bound by Scraggy Neck to the north and the North Falmouth mainland to the south. The main harbor basin narrows to a shallower inner harbor, which is separated from the main basin by a 600-ft-long stone jetty. The inner harbor narrows to a channel that is approximately 150 feet wide before widening again and opening into Squeteague Harbor, the innermost reach of the system. The average depth of the outer Harbor basin bottom is -7.3 feet mean low water (NAVD). The mean depth of the inner harbor is -4.5 feet NAVD while the mean depth of the Squeteague Harbor is 3.6 feet NAVD. The total surface coverage of the Megansett Harbor system including Squeteague Harbor is approximately 540 acres.

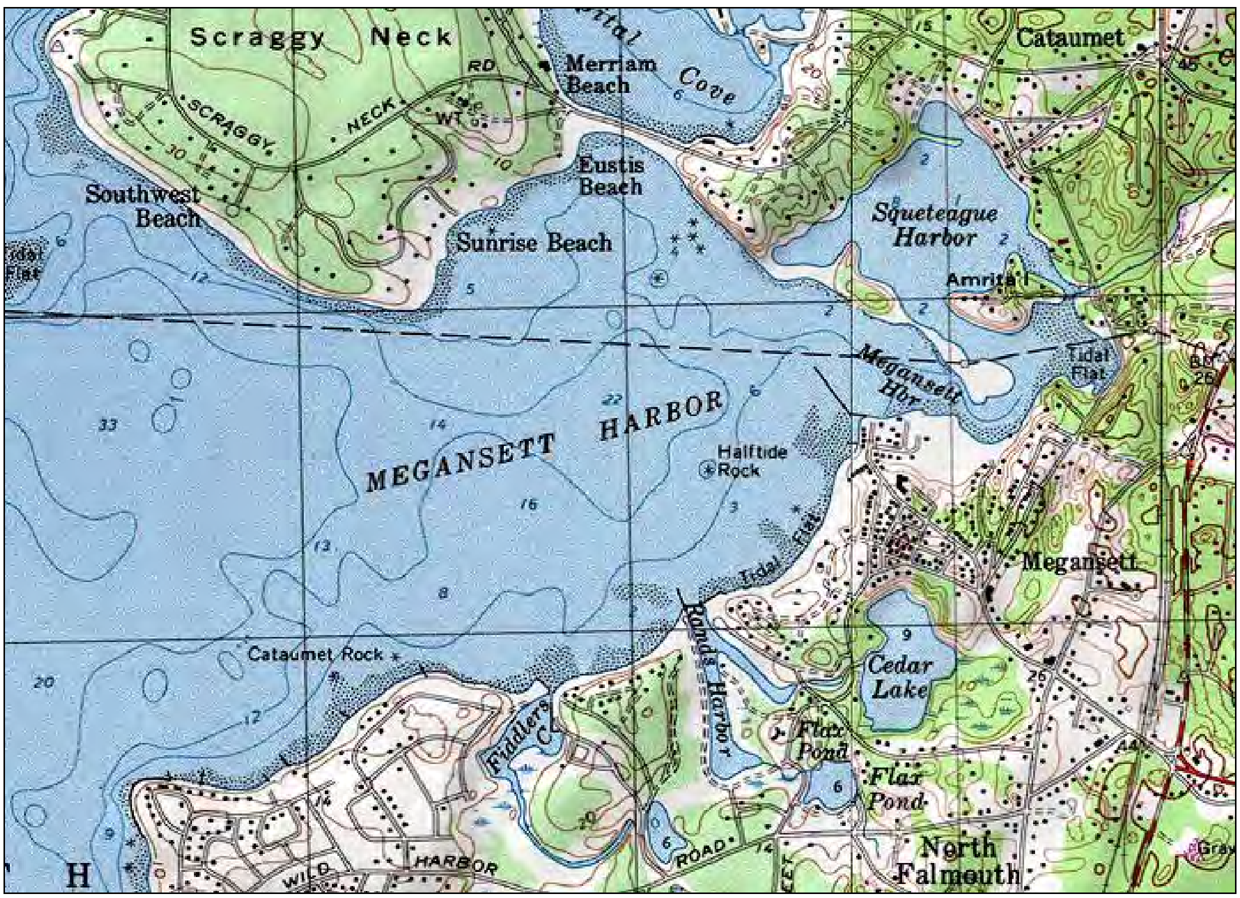


Figure V-1. Topographic map detail of Megansett Harbor, including Squeteague Harbor.

Tidal exchange with Buzzards Bay dominates circulation in the Harbor. From measurements made in the course of this study, the average offshore tide range is 4.4 feet. Tidal flushing is generally very efficient throughout the tidal reaches of the Harbor system as indicated by the lack of significant tide range attenuation in Squeteague Harbor, the upper-most portion of the system.

The hydrodynamic study of the Megansett Harbor system proceeded as two component efforts. In the first portion of the study, bathymetry and tide data were collected in order to accurately characterize the physical system, and to provide data necessary for the modeling portion of the study. The bathymetry survey of Megansett Harbor was performed to determine the variation of embayment depths throughout the system. This survey addressed the previous lack of adequate bathymetry data for this area. In addition to the bathymetry survey, tides were recorded at three stations for 30 days (Figure V-2). These tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of Megansett Harbor and its attached sub-embayments was developed in the second portion of this study. Using the bathymetry survey data, a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data from Buzzards Bay were used to define the open boundary condition that drives the circulation of the model, and data measured within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the real, physical system.

The calibrated hydrodynamic model of Megansett Harbor is an integral piece of water quality model developed in the next chapter of this report. In addition to its use as the hydrodynamic basis for the TN and salinity models, the calibrated hydrodynamic model is a useful tool that can be used to investigate the tidal properties of the system.

V.2 DATA COLLECTION AND ANALYSIS

The field data collection portion of this study was performed to characterize the physical properties of Megansett Harbor. Bathymetry data were collected throughout the system so that it could be accurately represented as a computer hydrodynamic model and flushing rates could be determined for the system. In addition to the bathymetry, tide data were also collected throughout the Harbor system (including the Squeteague Harbor in Bourne), in order to run the circulation model with real tides, and also to calibrate and verify its performance.

V.2.1 Bathymetry Data

A detailed bathymetric survey of Megansett and Squeteague Harbor was performed during November 2014. A fathometer was used to take continuous soundings of the bottom as the survey vessel moved through the water. Positioning data were collected using a RTK GPS. The actual survey paths followed by the survey craft are shown in Figure V-2. The NOAA GEODAS data archive was used to as a source of bathymetry data for offshore areas in Buzzards bay not covered in the 2014 survey.

The resulting bathymetric surface created by interpolating the data to a finite element mesh is shown in Figure V-3. All soundings were tide corrected using tide data collected in the system. The data all were rectified to the NAVD 88 vertical datum by the RTK GPS system.

Results from the survey show that the deepest point in Megansett Harbor is located at the opening to Buzzards Bay. The deepest depth measured in the course of the 2014 survey is -17.5 feet NAVD. Generally, the average depth of the whole system is moderately shallow, with a mean depth of -6.2 feet NAVD.

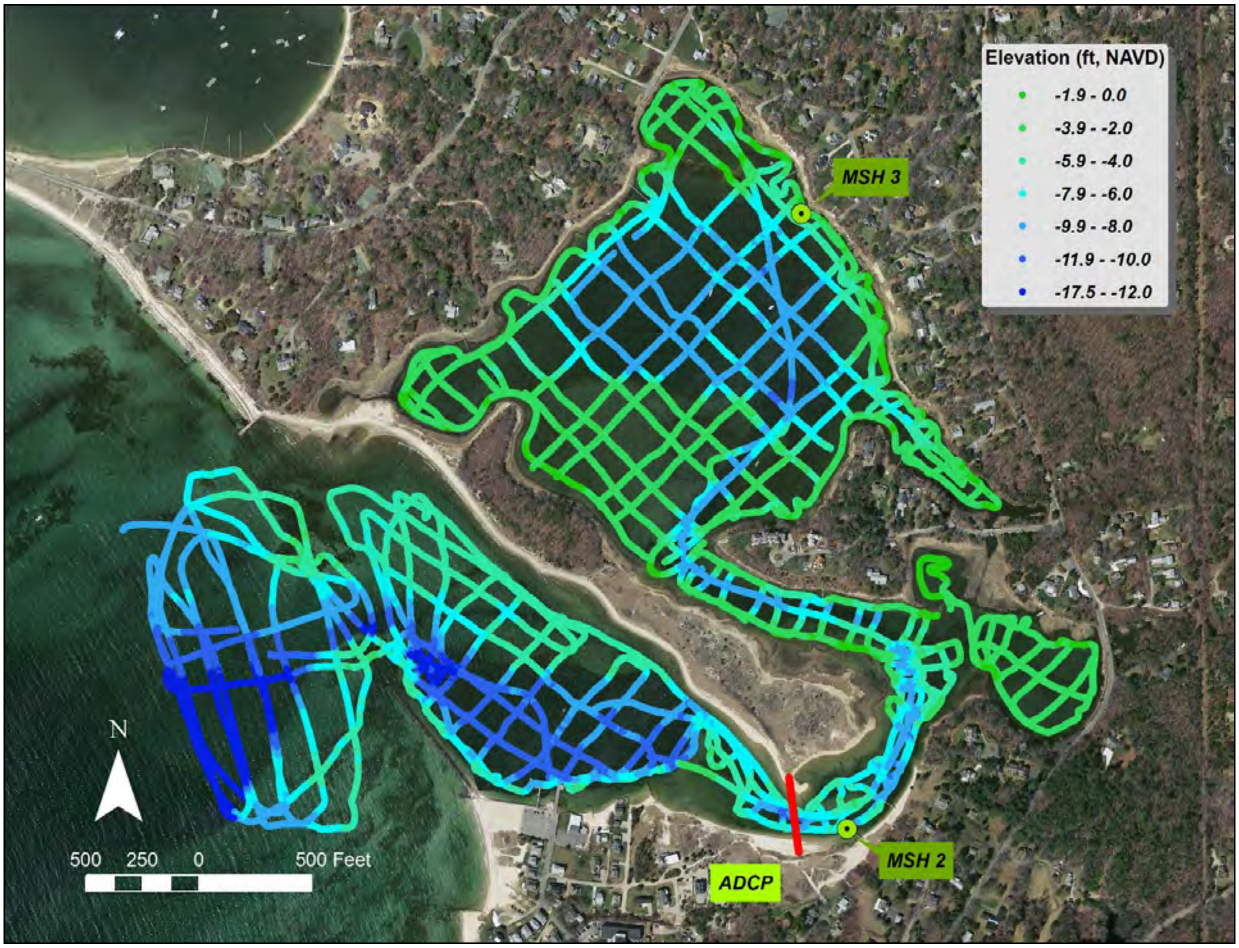


Figure V-2. Transects from the November 2014 bathymetry survey of Megansett Harbor. Green markers show the locations of the tide recorders deployed for this study. The cross-channel transect followed during the ADCP survey of tidal velocities is indicated using the solid red line.

V.2.2 Tide Data Collection and Analysis

Tide data records were collected concurrently at three gauging stations located in the outer Harbor (MSH1), at the inner harbor (MSH2) and Squeteague Harbor (MSH3). The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 33-day period between November 5 and December 8, 2014. The elevation of each gauge was surveyed relative to the NAVD vertical datum. The Outer Harbor tide record was used as the open boundary condition of the hydrodynamic model. Data from inside the system were used to calibrate the model.

Tide records longer than 29 days are necessary for a complete evaluation of tidal dynamics within the estuarine system. Although a one-month record likely does not include extreme high or low tides, it does provide an accurate basis for typical tidal conditions governed by both lunar and solar motion. For numerical modeling of hydrodynamics, the typical tide conditions associated with a one-month record are appropriate for driving tidal flows within the estuarine system.

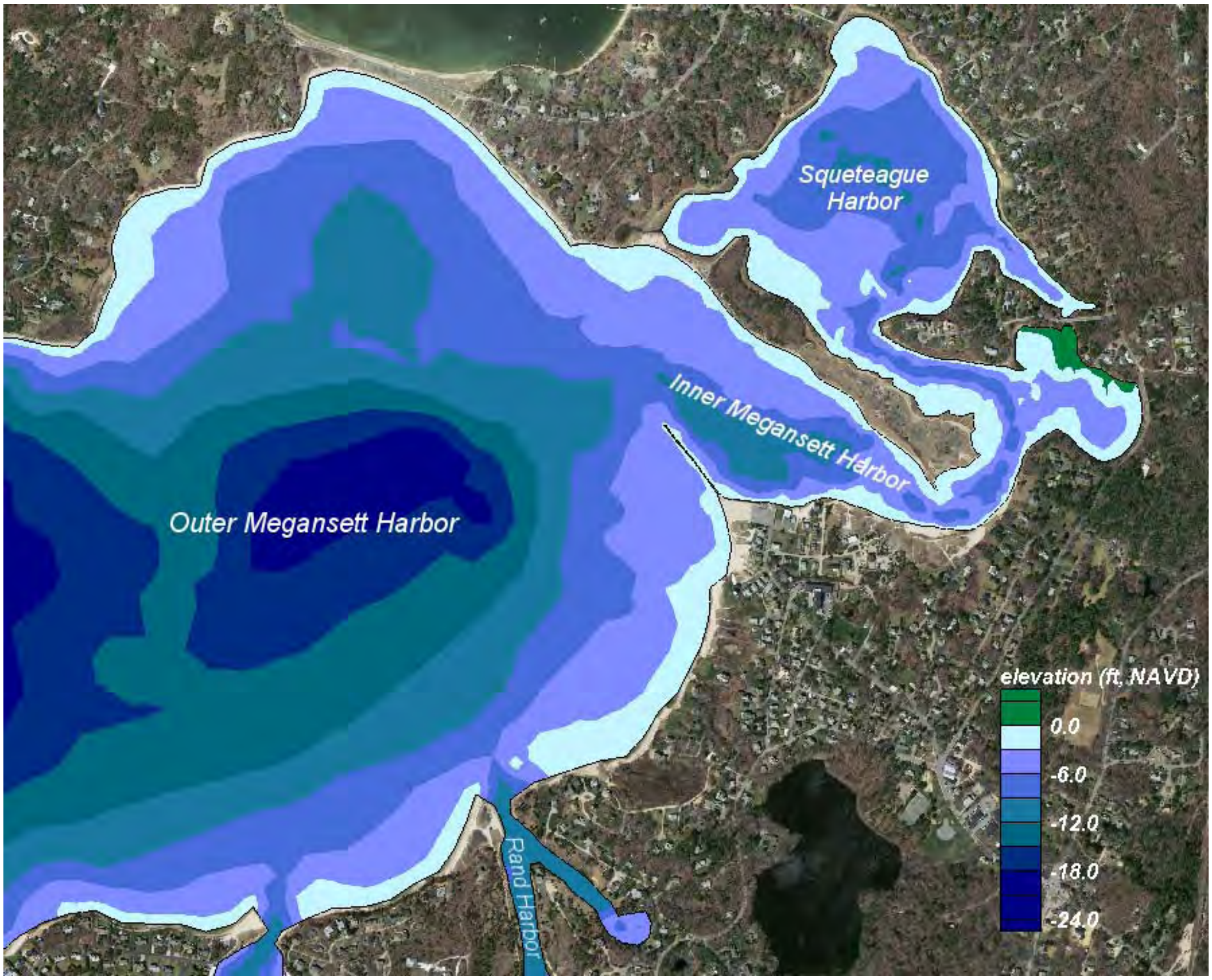


Figure V-3. Bathymetry data interpolated to the finite element mesh used with the RMA-2 hydrodynamic model. Contours represent the bottom elevation relative to mean low water (NAVD). The primary data source used to develop the grid mesh is the November 2014 survey of the system, with NOAA GEODAS data used for the deep basin of the outer Harbor.

Plots of the tide data from the three gauges are shown in Figure V-4 for the entire 30-day deployment. The spring-to-neap variation in tide range is discernible in these plots. The data record begins during a period of spring tides, where the maximum range is approximately 6 feet. A week later there is a period of neap tides, where the minimum range of 2 feet occurs on November 15, the day of the waning half-moon. Following this neap tide is a continuing cycle of neap and spring tides, though the transition is more muted than at the beginning of the month. The visual comparison between tide elevations offshore and at the different stations in the system shows that the tide amplitude does not change much, even in the inner-most reaches of the system.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 33-day records. These datums are presented in Table V-1. 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. The Mean Higher High (MHH) and Mean Lower Low (MLL) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW.

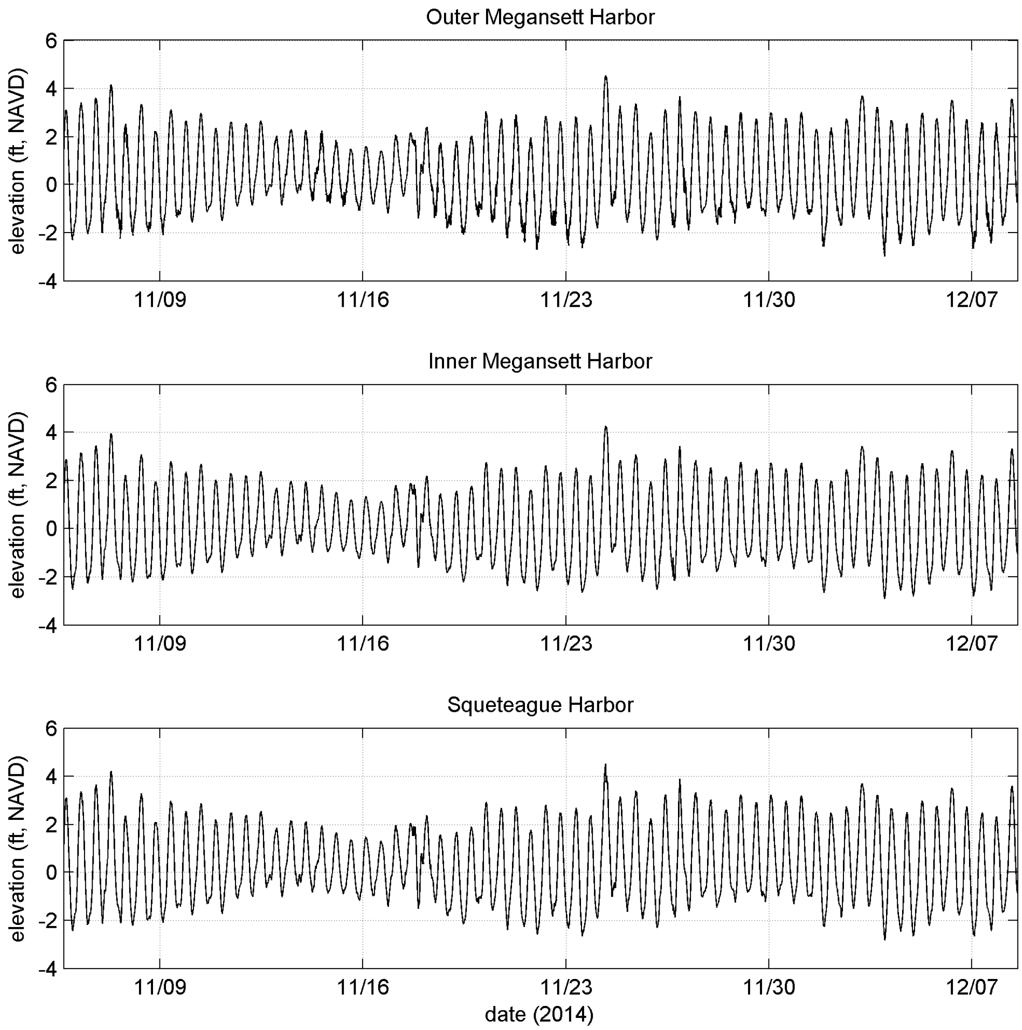


Figure V-4. Plots of observed tides for stations in Megansett Harbor, for the 33-day period between November 5 and December 8, 2014. All water levels are referenced to the NAVD vertical datum.

Little frictional damping occurs in this system. The mean tide range at all three stations is within ±0.1 feet. It is likely that the observed variation between gauges has more to do with gauge measurement error and elevation survey error than with real changes in the tide datum elevations between gauge stations (Figure V-5).

A more thorough harmonic analysis of the tidal time series was also performed to produce tidal amplitude and phase of the major tidal constituents, and provide assessments of hydrodynamic ‘efficiency’ of the system in terms of tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each system.

A harmonic analysis was performed on the time series from each gauge location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The observed astronomical tide 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. The amplitudes and phase of 21 known tidal constituents result from this procedure. Table V-2 presents the amplitudes of seven tidal constituents computed for the Megansett Harbor station records. The M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an offshore amplitude of 1.7 feet. The total range of the M_2 tide is twice the amplitude, or 3.4 feet.

Table V-1. Tide datums computed from 30-day records collected offshore and in the Megansett Harbor system in November and December 2014. Datum elevations are given relative to NGVD vertical datum.

Tide Datum	Outer Megansett Harbor (feet)	Inner Megansett Harbor (feet)	Squeteague Harbor (feet)
Maximum Tide	4.6	4.3	4.5
MHHW	2.9	2.7	2.9
MHW	2.7	2.4	2.7
MTL	0.5	0.3	0.5
MLW	-1.6	-1.8	-1.7
MLLW	-1.8	-2.0	-1.8
Minimum Tide	-3.0	-2.9	-2.8
Mean Range	4.4	4.2	4.3

The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.3 feet and 0.2 respectively. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, also contribute to the total tide signal, with amplitudes of 0.3 feet and 0.4 feet, respectively. The M_4 and M_6 tides are higher frequency harmonics of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water.

Generally, it can be seen that as the total tide range is the same through the system, the amplitude of the individual tide constituents remains the same also. This is true even of the M_4 and M_6 overtide amplitudes, which indicate little energy loss due to tidal damping of the M_2.

Along with the consistent constituent amplitudes across the Harbor and its sub-embayments, there is a corresponding lack of change in the timing of the tides through the system. Table V-3 shows the delay of the M_2 at different points in the Megansett Harbor system, relative to the timing of the M_2 constituent in the outer Harbor. At both inner gauges, the measured delay (about 3 minutes) of the M_2 is less than the time step of the data record (10 minutes). This indicates that the phasing of the tides is essentially the same, and that there is no significant phase delay across the system.

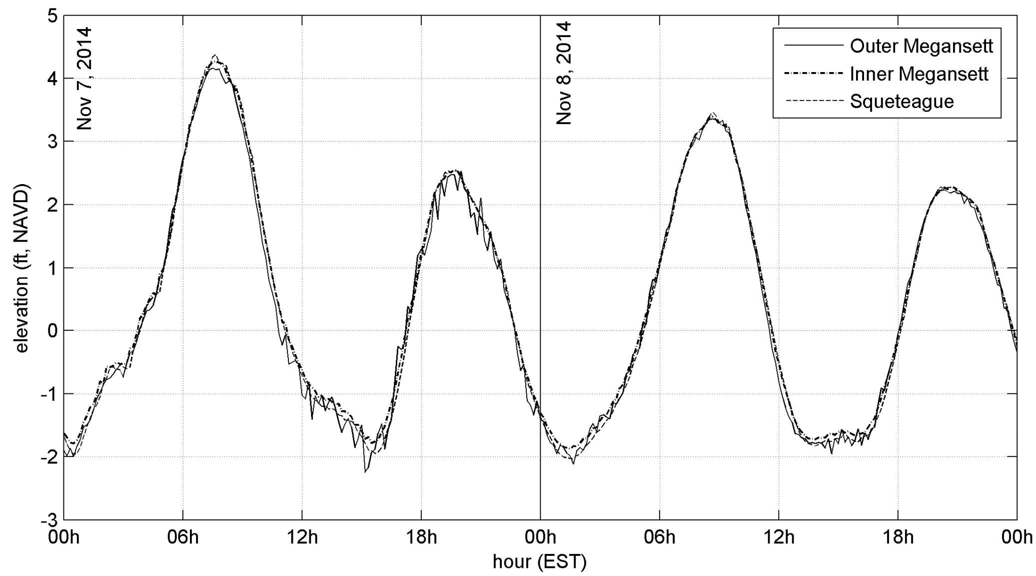


Figure V-5. Two-day tide plot showing tides measured at stations in the Megansett Harbor system.

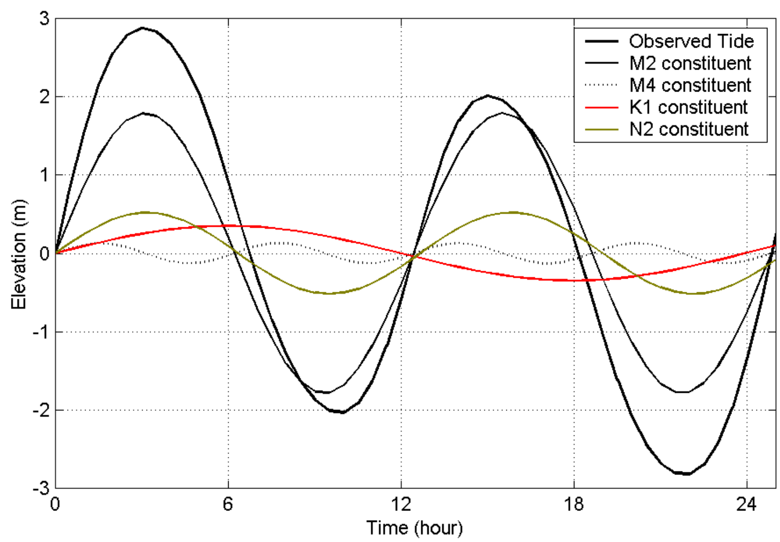


Figure V-6. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-2. Tidal Constituents computed for tide stations in the Megansett Harbor system and November and December 2014.

	Amplitude (feet)						
Constituent	M_2	M_4	M_6	S_2	N_2	K_1	O_1
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82
Outer Megansett	1.93	0.28	0.04	0.39	0.39	0.21	0.16
Inner Megansett	1.91	0.28	0.05	0.39	0.39	0.21	0.15
Squeteague	1.95	0.29	0.06	0.40	0.39	0.21	0.15

In addition to the tidal analysis, the data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. These other processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow.

The results of an analysis to determine the energy distribution (or variance) of the measured water elevation records for the gauge records in Megansett Harbor compared to the energy content the astronomical tidal signal (re-created by summing the contributions from the 21 constituents determined by the harmonic analysis) is presented in Table V-4. Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from the outer Megansett station, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

Table V-4 shows that the variance of tidal energy is practically the same at all three gauging stations in the Harbor, and that the tidal contribution to the total variance is the same percentage (approximately 93 percent) at all three stations as well. Though there are some larger deviations between the measured and astronomical tide records, the mean non-tidal variance of the complete records at each station indicate that non-tidal effects on the total observed water level changes are not a large contributor to the total measured tide, on average.

Table V-3. M_2 tidal constituent phase delay (relative to Megansett Harbor) for gauge locations in the Megansett Harbor system, determined from measured tide data.

Station	Delay (minutes)
Inner Megansett Harbor	3.4
Squeteague Harbor	3.2

Table V-4. Percentages of Tidal versus Non-Tidal Energy for stations in the Megansett Harbor system and Buzzards Bay, November to December 2014 2005.

TDR Location	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Outer Megansett	2.4	93.2	6.8
Inner Megansett	2.3	93.5	6.5
Squeteague Harbor	2.4	93.5	6.5

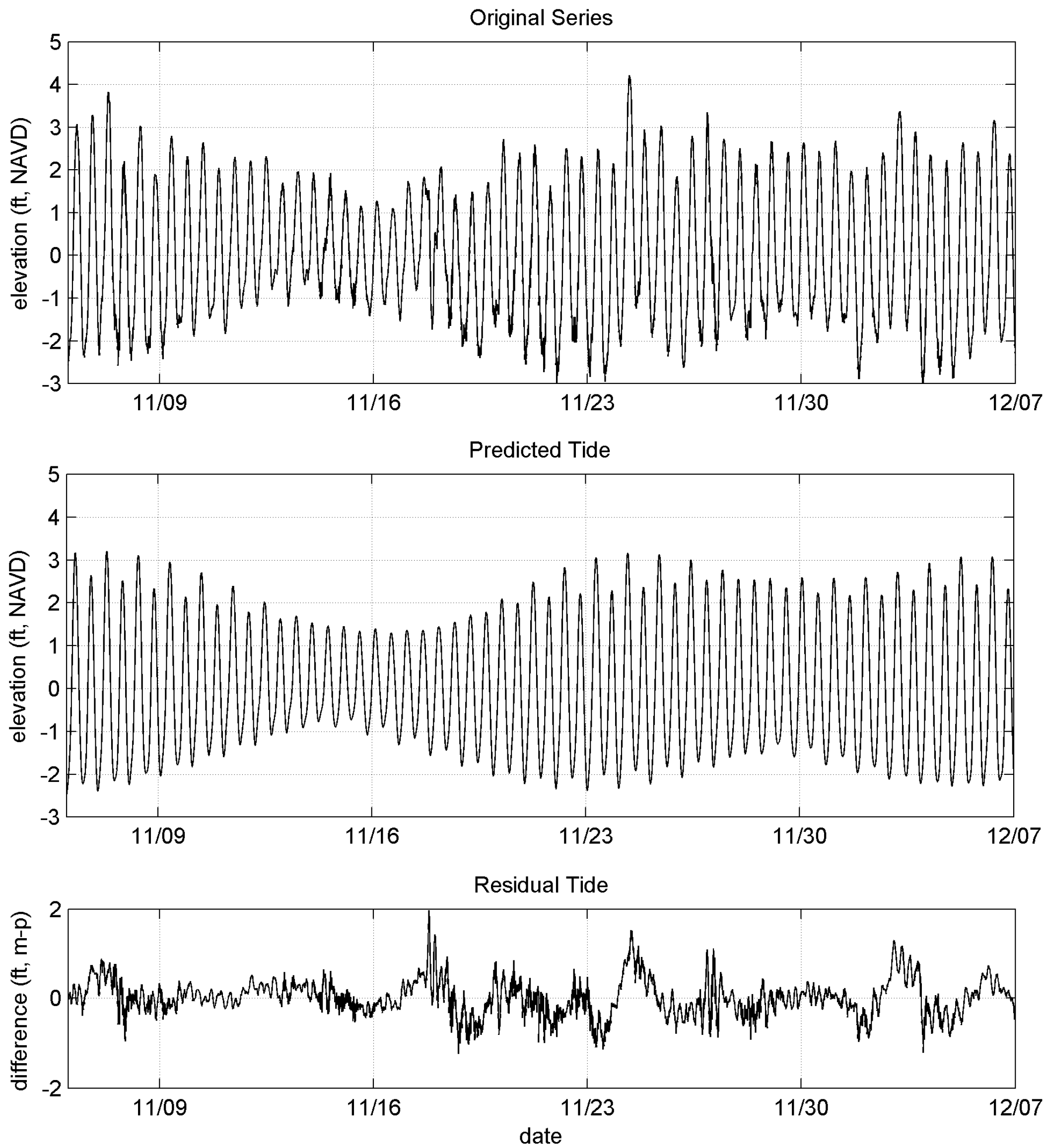


Figure V-7. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 21 individual tide constituents determine in the harmonic analysis of the outer Megansett Harbor gauge data. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (r=m-p).

V.3 HYDRODYNAMIC MODELING

For the modeling of the Megansett Harbor system, Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in the harbor system. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. 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 on Cape Cod, including West Falmouth Harbor, Popponesset Bay, Chatham embayments (Kelley, *et al*, 2001), Falmouth "finger" Ponds (Howes *et al*, 2005), Three Bays (Howes *et al*, 2005) and Barnstable Harbor (Wood, *et al*, 1999).

V.3.1 Model Theory

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

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

The extent of each finite element grid was generated using 2005 and 2009 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 Megansett Harbor grid based on the tide gauge data collected offshore at the outer harbor tide station. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several model calibration simulations for the system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. Mass GIS 2013 digital aerial orthophotos and the 2014 bathymetry survey data were imported to SMS, and a finite element grid was generated to represent the estuary. The aerial photograph was used to determine the land boundary of the system, as well as determine the surface coverage of salt marsh. The bathymetry data were interpolated to the developed finite element mesh of the system. The completed grid consists of 5,507 nodes, which describe 2,032 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth is -22ft (NGVD) along the open boundary of the grid in Buzzards Bay. The completed grid mesh of the Megansett Harbor system is shown in Figure V-8.

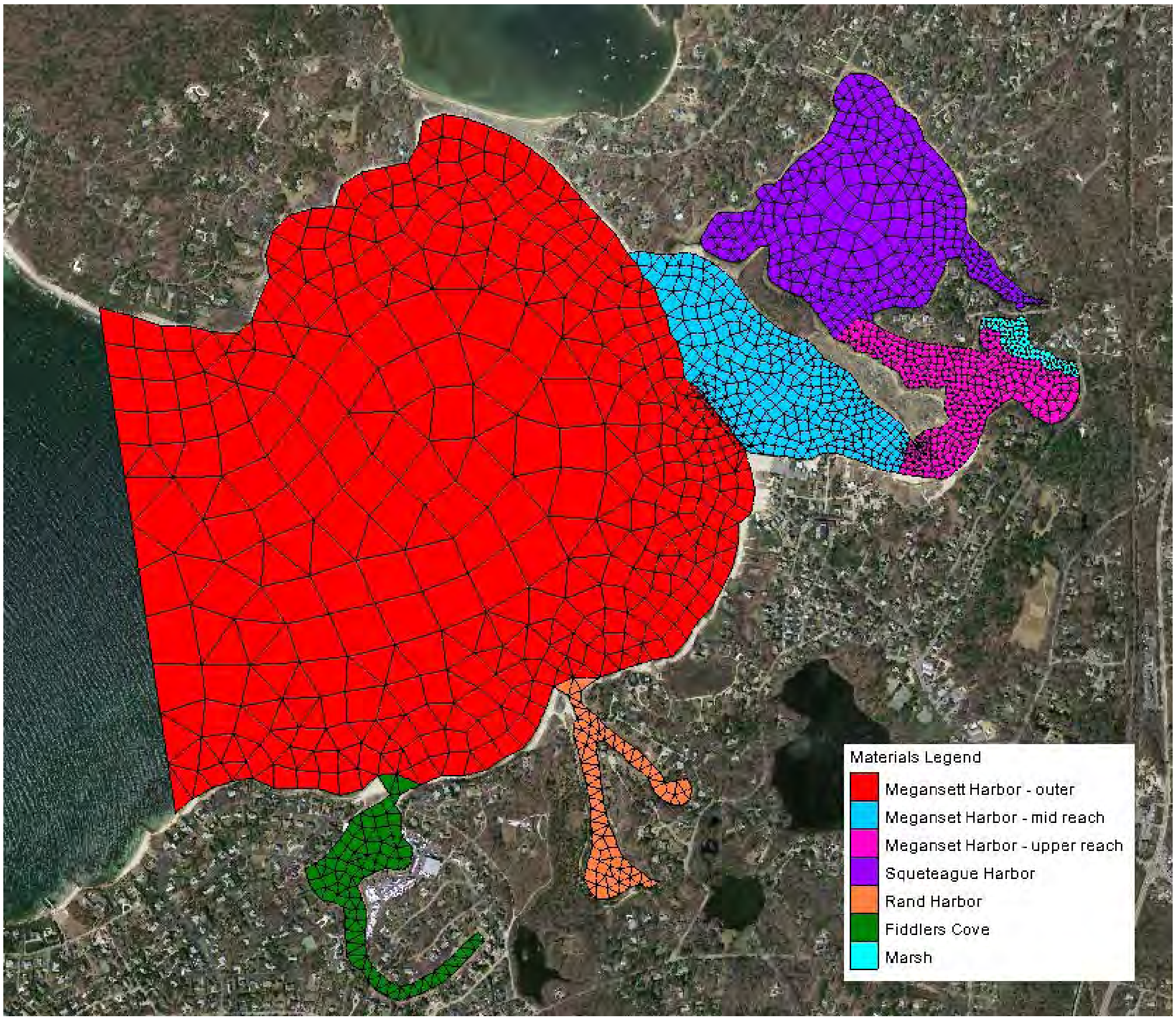


Figure V-8. Plot of hydrodynamic model grid mesh for Megansett Harbor. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Megansett Harbor. To maintain continuity with the application of the MEP approach in other embayment systems, areas of marsh were included in the model even though they represent an insignificant portion of the total surface area of this system. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Grid resolution is generally governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution is employed where complex flow patterns are expected, generally near the inlet. 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

Three types of boundary conditions were employed for the RMA-2 model of the Megansett Harbor system: 1) "slip" boundaries, 2) tidal elevation boundaries, and 3) constant flow input boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. A tidal boundary condition was specified at the boundary with Buzzards Bay. TDR measurements provided the required data. The rise and fall of the tide in the Bay is the primary driving force for estuarine circulation in this system. Dynamic (time-varying) model simulations specified a new water surface elevation at the open boundary of the Megansett Harbor grid every model time step. The model runs of Megansett Harbor used a 10-minute time step, which the same as the 10-minute sampling rate of the measured tide data. Details concerning the constant flow input boundary conditions included in the hydro model are discussed in Chapter VI.

V.3.2.3 Calibration

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

Calibration of the hydrodynamic model required a close match between the modeled and measured tides from stations inside the system (i.e., from the TDR deployments). Initially, the model was calibrated to obtain visual agreement between modeled and measured tides.

Once visual agreement was achieved, an 14-day period (27 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section 2. The 14-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibration was performed for a 14-day period beginning November 10, 2014 at 2200 EST. This representative time period included one full cycle between spring and neap periods.

After the model was calibrated, an additional verification run was made in order test the model performance in a time period outside of the calibration period. The model verification was performed for the eight-day period beginning November 30, 2014 at 1200 EDT.

The calibrated model was used to analyze existing detailed flow patterns and compute residence times. The flushing analysis is based on the same 14-day time period used for model calibration. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire seven-day simulation. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events.

V.3.2.3.a Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient, and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.025 and 0.070 were specified for all element material types. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels and marsh plains with higher friction (Henderson, 1966).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning’s coefficients were matched to bottom type. For example, lower friction coefficients were specified for main basin of Megansett Harbor, versus the marsh plain areas of the inner harbor, which provides greater flow resistance. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992), and values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-5.

Table V-5. Manning’s Roughness and eddy viscosity coefficients used in simulations of the Megansett Harbor system. These embayment delineations correspond to the material type areas shown in Figure V-8.

System Embayment	bottom friction	eddy viscosity lb-sec/ft^2
Megansett Harbor – outer	0.025	80
Megansett Harbor – mid reach	0.025	50
Megansett Harbor – upper reach	0.025	50
Squeteague Harbor	0.025	50
Rands Canal	0.025	50
Fiddlers Cove	0.025	50
Megansett Harbor marsh	0.070	50

V.3.2.3.b Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set to 50 lb-sec/ft^2 (Table V-5). A higher value of 80 lb-sec/ft^2 was used for the open area of outer Megansett Harbor.

V.3.2.3.c Marsh porosity processes

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

V.3.2.3.d Comparison of modeled tides and measured tide data

A best-fit of model output for the measured data was achieved using the aforementioned values for friction and turbulent exchange. Figures V-9 through V-11 illustrate sections the 14-day simulation periods for the calibration model. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the system embayments. Four tidal constituents were selected for constituent comparison: the K_1, M_2, M_4 and M_6. Measured tidal constituent amplitudes are shown in Tables V-6 and V-7 for the calibration and verification simulations. The constituent amplitudes shown in these table differ from those in Table V-2 because constituents were computed for only the shorter sub-sections of the 30-days represented in Table V-2. In Tables V-6 and V-7, error statistics are shown for the calibration and verification.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The errors associated with tidal constituent amplitude for both the calibration and verification simulations were of the order 0.01 ft, which is of the same order magnitude of the accuracy of the tide gauges (0.032 ft). Time lag errors for the main estuary reach were less than the time increment resolved by the model and tide data (10 minutes), indicating good agreement between the model and data. The skill of the model calibration is also demonstrated by the high degree of correlation (R^2) and low RMS error shown in Table V-8 for all stations.

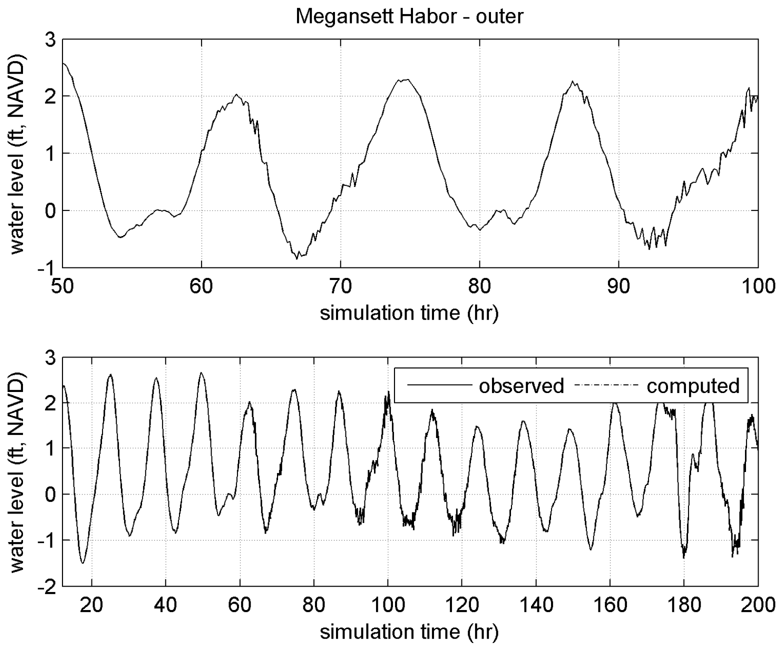


Figure V-9. Comparison of model output and measured tides for the TDR location offshore in outer Megansett Harbor (MSH-1) for the final calibration model run (November 10, 2014 at 22:00 EST). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

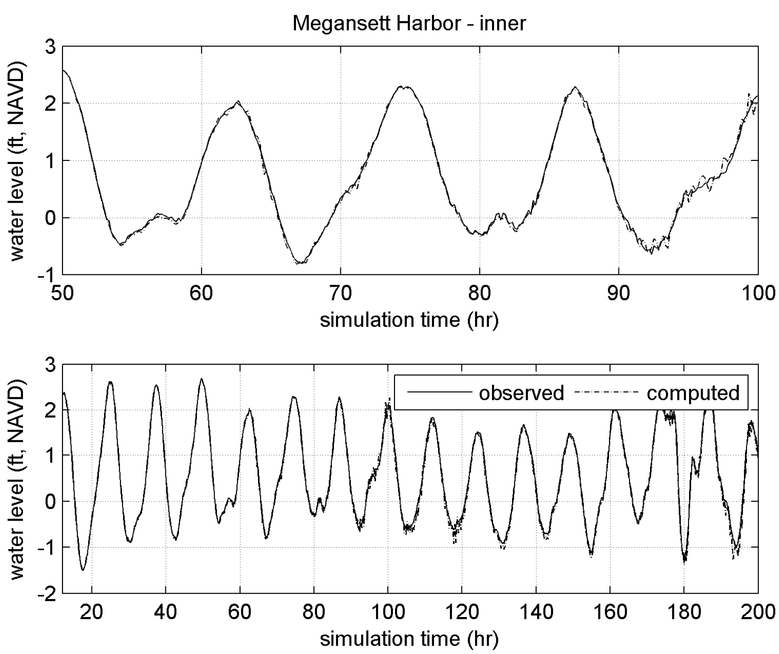


Figure V-10. Comparison of model output and measured tides for the TDR location in the inner harbor (MSH-2) for the final calibration model run (November 10, 2014 at 22:00 EST). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot

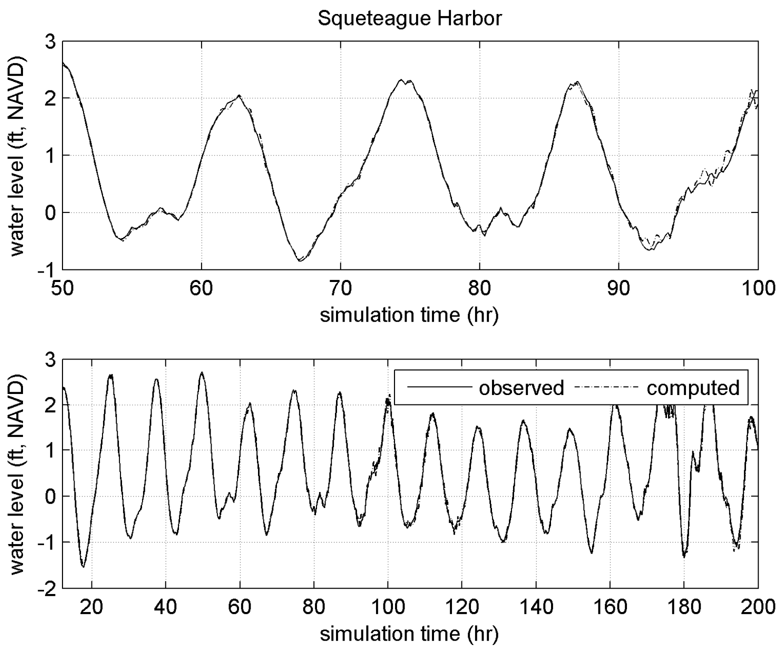


Figure V-11. Comparison of model output and measured tides for the TDR location in Squeteague Harbor (MSH-3) for the final calibration model run (November 10, 2014 at 22:00 EST). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot

Table V-6. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for Megansett Harbor, during modeled calibration time period.

Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Outer Megansett	1.41	0.25	0.04	0.11	10.4	50.8
Inner Megansett	1.40	0.25	0.05	0.11	11.7	53.1
Squeteague	1.42	0.25	0.06	0.11	13.1	54.0
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Outer Megansett	1.41	0.25	0.04	0.11	10.5	51.0
Inner Megansett	1.42	0.24	0.05	0.11	11.9	51.3
Squeteague	1.42	0.24	0.06	0.11	14.1	51.9
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Outer Megansett	0.00	0.00	0.00	0.00	-0.3	-0.2
Inner Megansett	-0.02	0.01	0.00	0.00	-0.4	1.9
Squeteague	0.00	0.01	0.00	0.00	-2.2	2.1

Table V-7. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for Megansett Harbor, during modeled verification time period (November 30, 2014 at 12:00 and December 8, 2014 at 12:00).

Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Outer Megansett	2.27	0.30	0.06	0.30	76.1	146.9
Inner Megansett	2.25	0.31	0.07	0.29	77.8	146.5
Squeteague	2.30	0.32	0.08	0.30	79.6	146.6
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Outer Megansett	2.27	0.30	0.06	0.30	76.2	147.1
Inner Megansett	2.27	0.31	0.06	0.29	77.8	146.5
Squeteague	2.26	0.32	0.07	0.29	79.6	146.6
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Outer Megansett	0.00	0.00	0.00	0.00	-0.2	-0.2
Inner Megansett	-0.02	0.00	0.01	0.00	-0.1	1.6
Squeteague	0.04	0.00	0.01	0.01	-1.3	3.8

Table V-8. Error statistics for the Megansett Harbor hydrodynamic model, for model calibration and verification model runs. Error estimate provided in feet.

	Calibration		Verification	
	R^2	RMS error	R^2	RMS error
Outer Megansett	1.00	0.00	1.00	0.00
Inner Megansett	0.99	0.10	1.00	0.10
Squeteague Harbor	0.99	0.08	0.99	0.20

V.3.2.3.e ADCP corroboration of hydrodynamic model

An additional evaluation of model corroboration with measured data was performed by comparing model flow rates and ADCP field measurements. An ADCP survey of flow velocities at the narrowest cross-section of the Inner Megansett channel (Figure V-2) was executed on November 11, 2014. During this survey, velocities through the channel cross-section were measured by a boat-mounted ADCP that traversed the inlet 172 times during the course of the survey day. Flow rates were output from the model at a continuity line placed across the channel in the same location as the ADCP transect. The comparison of ADCP measurement-derived flow rates and model output is presented in Figure V-12. The comparison between model output and ADCP flowrates is very good, further indicating that the hydrodynamic model adequately represents the physics of the real system. The R^2 correlation between model output and measurements is 0.89, and the RMS error of the model output is 178 ft^3/sec.

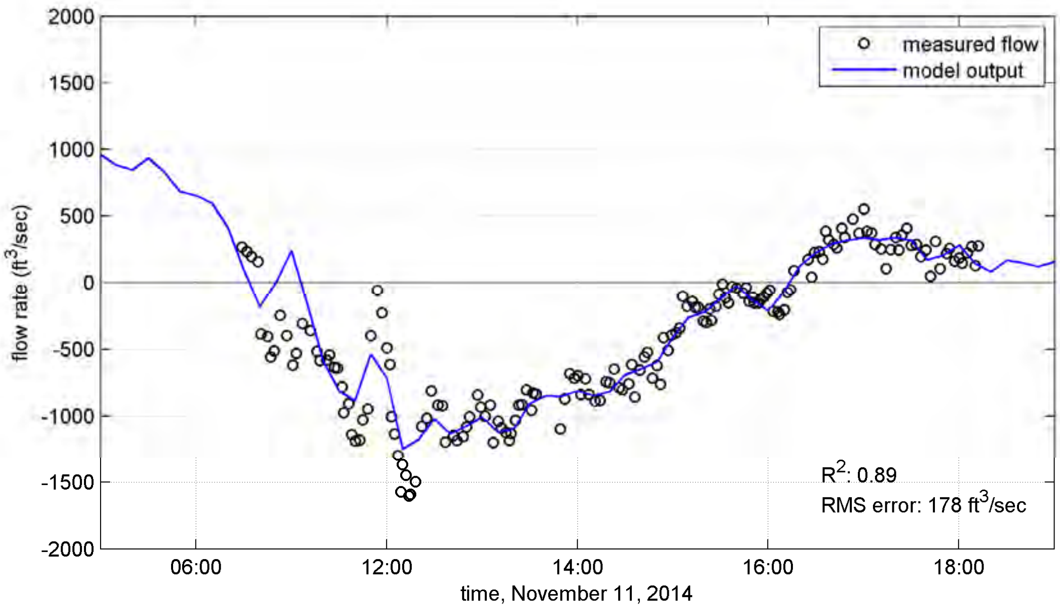


Figure V-12. Comparison of flow rates determined using ADCP velocity data and modeled flow rates at the survey transect in inner Megansett Harbor (Figure V-2).

V.3.4 Model Circulation Characteristics

The final calibrated model serves as a useful tool in investigating the circulation characteristics of the Megansett Harbor 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. As an example, Figure V-13 shows color contours and vectors that indicate velocity during a single model time step, during a period of maximum flood currents at the inlet.

As another example, from the calibration model run of the Megansett Harbor system, the total flow rate of water flowing through the narrowest portion of the Inner Megansett Harbor Channel can be determined with the hydrodynamic model, similar to what was done for the ADCP corroboration of model results. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-14. During spring tides, the maximum flood flow rates reach 2000 ft^3/sec in the channel. Maximum ebb flow rates during spring tides are similar.

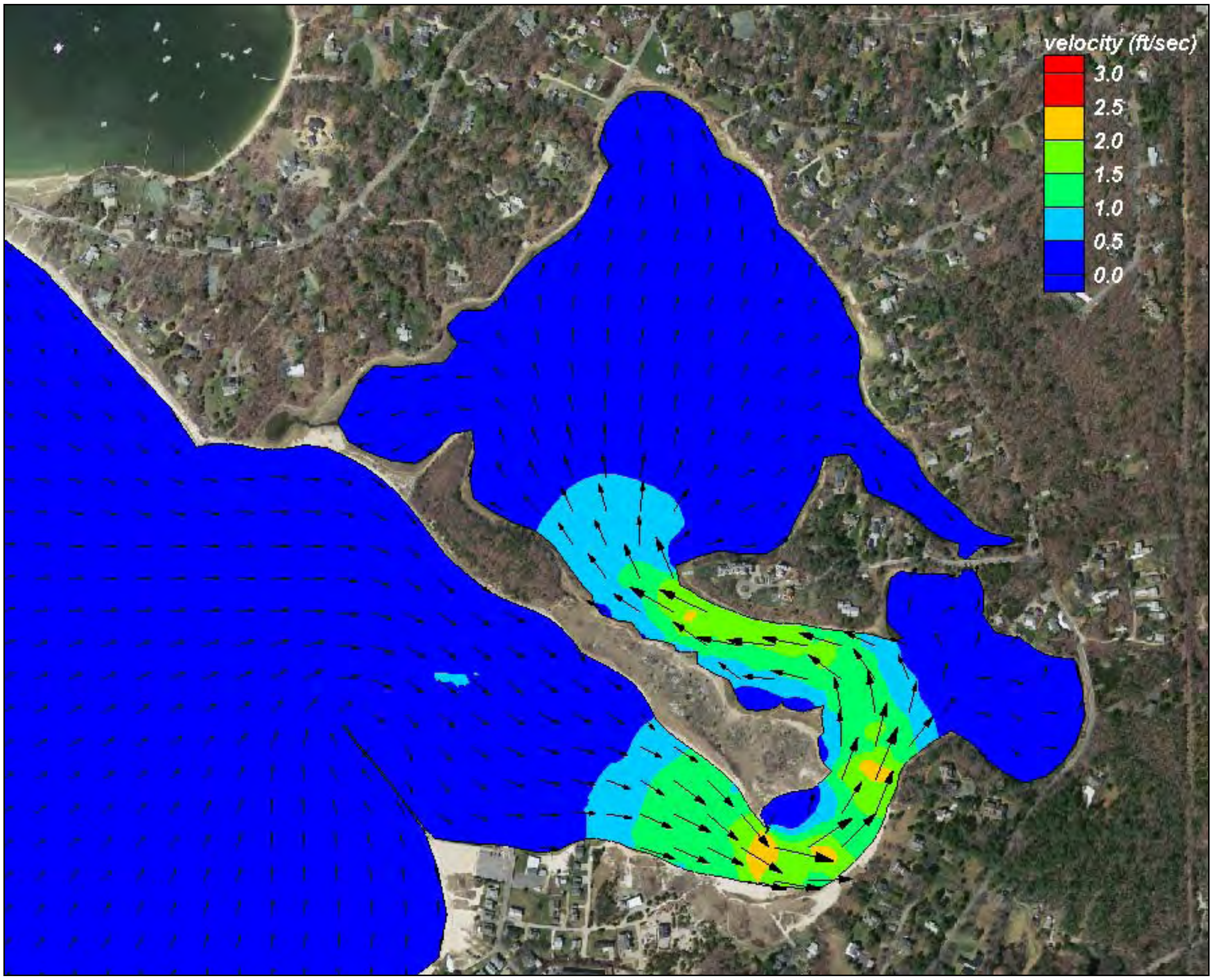


Figure V-13. Example of Megansett Harbor hydrodynamic model output for a single time step during a flooding tide. Color contours indicate velocity magnitude, and vectors indicate the direction of flow. Areas of marsh are also shown as the solid black lines within the model domain.

Using the velocities computed in the model, an investigation of the flood or ebb dominance of different areas in the Megansett Harbor system can be performed. Marsh systems are typically flood dominant, meaning that maximum flood tide velocities are greater than during the ebb portion of the tide. Flood dominance indicates a tendency to collect and trap sediment, which is required to maintain healthy marsh resources. The entrapment and retention of sediment and organic material is necessary to replenish material lost to organic decay and also to stay ahead of rising sea levels.

Flood or ebb dominance in channels of a tidal system can be determined by performing a harmonic analysis of tidal currents. A discussion of the method of relative phase determination is presented in Friedrichs and Aubrey (1988). For this method, the M_2 and M_4 tidal constituents of a tidal velocity time series are computed, similar to the tidal elevation constituents presented in Section V.3.2.

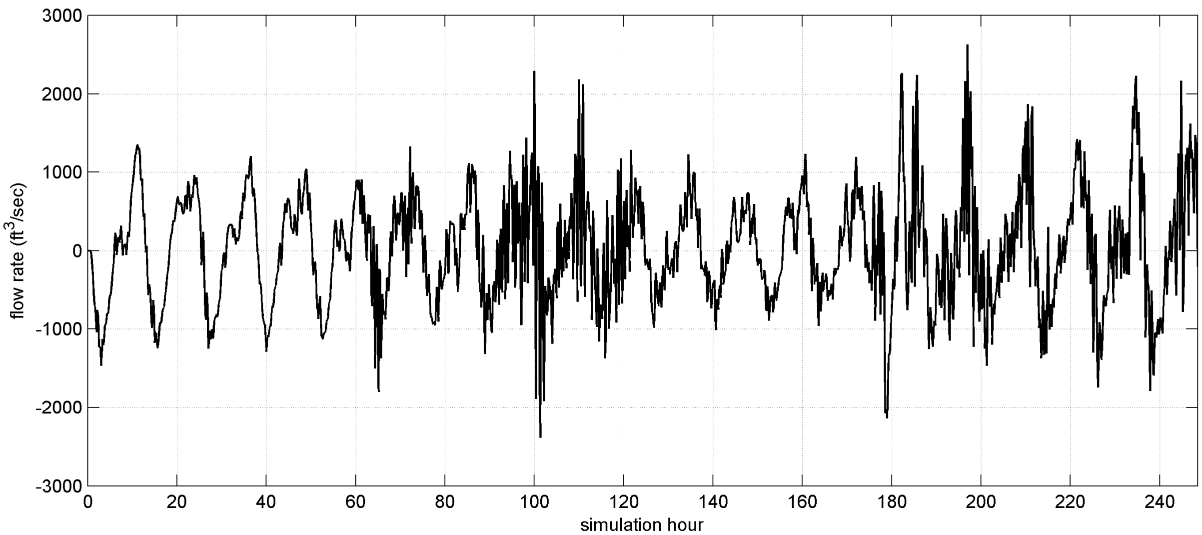


Figure V-14. Time variation of computed flow rates at the Inner Megansett Harbor channel. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flow indicated flooding tide flows, while negative flow indicates ebbing tide flows.

The relative phase difference is computed as the difference between two times the M_2 phase and the phase of the M_4, expressed as $\Phi=2M_2-M_4$. If Φ is between 270 and 90 degrees ($-90<\Phi<90$), then the channel is characterized as being flood dominant, and peak flood velocities will be greater than for peak ebb. Alternately, if Φ were between 90 and 270 degrees ($90<\Phi<270$), then the channel would be ebb dominant. If Φ is exactly 90 or 270 degrees, neither flood nor ebb dominance occurs. For Φ equal to exactly 0 or 180 degrees, maximum tidal distortion occurs and the velocity residuals of a channel are greatest. This relative phase relationship is presented graphically in Figure V-15.

Though this method of tidal constituent analysis provides similar results to a visual inspection of a velocity record (e.g., by comparing peak ebb and flood velocities), it allows a more exact characterization of the tidal processes. By this analysis technique, a channel can be characterized as being strongly, moderately, or weakly flood or ebb dominant.

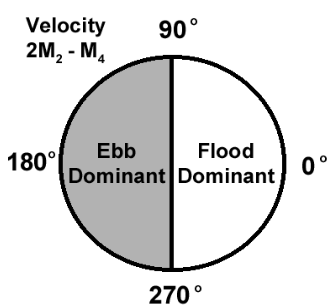


Figure V-15. Relative velocity phase relationship of M2 and M4 tidal velocity constituents and characteristic dominance, indicated on the unit circle. Relative phase is computed as the difference of two times the M2 phase and the M4 phase (2M2-M4). A relative phase of exactly 90 or 270 degrees indicates a symmetric tide, which is neither flood nor ebb dominant.

The results of this velocity analysis of model output at the Megansett Harbor inlet channel show that that the system is moderately ebb dominant. The $2M_2$-M_4 phase difference is determined to be 230.3 degrees. The open areas of Buzzards Bay tend to be ebb dominant due to the characteristics of the tide in the Bay. Since there is little attenuation of the tide between the outer and inner areas of Megansett Harbor, the ebb dominance of the Bay is easily transmitted to the inner reaches of the harbor. Other nearby systems that experience a greater degree of tidal attenuation (e.g., Wild Harbor River, also in Falmouth) tend to exhibit ebb dominance at the entrance to the system, and flood dominance in the upper reaches.

V.3.5 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 the modeled Megansett Harbor system is tidal exchange. A rising tide offshore in Buzzards Bay creates a slope in water surface from the ocean into the upper-most reaches of the modeled system. Consequently, water flows into (floods) the system. Similarly, the estuary drains into the open waters of the Bay on an ebbing tide. This exchange of water between the system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of the harbor 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 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 Squeteague Harbor as an example, the **system residence time** is the average time required for water to migrate from Squeteague Harbor, through the inner section of Megansett Harbor, and into Buzzards Bay through the outer area of Megansett Harbor, where the **local residence time** is the average time required for water to migrate from Squeteague Harbor to only the inner section of Megansett Harbor (not all the way to the Bay). Local residence times for each sub-embayment are computed as:

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

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

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

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. It is impossible to evaluate an estuary's health based solely on flushing rates. 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 is obtained from the calibrated hydrodynamic model in the following section of this report (Section VI) by extending the model to include pollutant/nutrient dispersion. The water quality model provides an additional valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Harbor system.

Since the calibrated RMA-2 model simulated accurate two-dimensional hydrodynamics in the system, model results were used to compute residence times. Residence times were computed for the entire estuary, as well as three subdivisions of the system. 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 the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Model divisions used to define the system sub-embayments include 1) the entire Megansett Harbor system, 2) inner Megansett Harbor including Squeteague Harbor, and 3) Squeteague Harbor by itself. These system divisions follow the model material type areas designated in Figure V-8. Sub-embayment mean volumes and tide prisms are presented in Table V-9.

Table V-9. Embayment mean volumes and average tidal prism during simulation period for the Megansett Harbor system.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Megansett Harbor System	269,638,200	85,502,500
Inner Megansett Harbor	31,660,800	18,026,300
Squeteague Harbor	15,653,800	8,546,300

Residence times were averaged for the tidal cycles comprising a representative 14 day period (27 tide cycles), and are listed in Table V-10. The modeled time period used to compute the flushing rates started November 10, 2014 , similar to the model calibration period, and included the transition from neap to spring tide conditions. The RMA-2 model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume.

Since the 14 day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

Table V-10. Computed System and Local residence times for embayments in the Megansett Harbor system.

Embayment	Local Residence Time (days)	System Residence Time (days)
Megansett Harbor System	1.6	1.6
Inner Megansett Harbor	7.7	0.9
Squeteague Harbor	16.3	0.9

The computed flushing rates for the Harbor system show that as a whole, the system flushes moderately well. A flushing time of 1.6 days for the entire estuary shows that on average, water is resident in the system for less than two days. The inner reaches of the Harbor system have local flushing times that are less than one day.

The generally low local residence times in all areas of the Megansett Harbor system show that they would likely have good water quality if the system water with which it exchanges also has good water quality. For example, the water quality of Squeteague Harbor would likely be good as long as the water quality of the outer Megansett Harbor basin was also good. Actual water quality would still also depend upon the total nutrient load to each embayment.

For the smaller sub-embayments of the Harbor system, computed system residence times are typically one to four orders of magnitude longer than their corresponding local residence time. System residence times provide a qualitative measure that helps to identify the relative sensitivity of different sub-embayments to nutrient loading.

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 Megansett Harbor system. Possible errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. In this study, the most significant errors associated with the bathymetry data result from the process of interpolating the data to the finite element mesh, which was the basis for all the flushing volumes used in the analysis. In addition, limited topographic measurements were available in some of the smaller sub-embayments of the system.

Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. However, water exiting a small sub-embayment on a relatively calm day may not completely mix with estuarine waters. In this case, the "strong littoral drift" assumption would lead to an under-prediction of residence time. Since littoral drift along the shoreline of Buzzards Bay typically is strong because of the effects of the local winds and tidal induced mixing, the "strong littoral drift" assumption will only cause 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 Megansett Harbor system. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the embayments were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated hydrodynamic model representing the transport of water within the Megansett Harbor system. Files of node locations and node connectivity for the RMA-2V model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic model output used for the water quality model calibration was the 14 day (27 tide cycle) period beginning November 10, 2014 1630 EDT. This period overlaps with that used in the flushing analysis presented in Chapter V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic "steady state", and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

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

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. The multi-year averages present the "best" comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. 14 years of data (collected between 2000 and 2013) were available for stations in the harbor.

Table VI-1. Measured data and modeled nitrogen concentrations for the Megansett Harbor estuarine system (at stations indicated in Figure VI-1). All concentrations are given in mg/L N. "Data mean" values are calculated as the average of all measurements. Data represented in this table were collected in the summers of 2000 through 2013.

Sub-Embayment	Monitoring station	Data Mean	s.d. all data	N	model min	model max	model average
Outer Megansett	MG1	0.407	0.081	46	0.365	0.438	0.394
Outer Megansett	MG2	0.344	0.066	48	0.352	0.379	0.363
Outer Megansett	MG3	0.358	0.072	93	0.334	0.366	0.350
Outer Megansett	MG4	0.332	0.071	47	0.328	0.342	0.331
Inner Megansett	SQ1	0.452	0.070	92	0.377	0.445	0.415
Squeteague H.	SQ2	0.468	0.105	42	0.416	0.449	0.432

MG1 Megansett Harbor Annual TN means													
2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
0.305	0.488	0.392	0.451	0.397	0.347	0.422	0.397	0.427	0.295	0.467	0.334	0.471	0.467
MG2 Megansett Harbor Annual TN means													
2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
0.316	0.379	0.323	0.345	0.352	0.306	0.356	0.389	0.363	0.267	0.359	0.239	0.379	0.380
MG3 Megansett Harbor Annual TN means													
2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
0.258	0.394	0.367	0.385	0.307	0.354	0.356	0.414	0.393	0.269	0.380	0.326	0.409	0.384
MG4 Megansett Harbor Annual TN means													
2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
0.265	0.353	0.403	0.350	0.352	0.342	0.372	0.357	0.382	0.354	0.381	0.249	0.389	0.327
SQ1 Squeteague Harbor Annual TN means													
2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
0.398	0.470	0.476	0.476	0.410	0.408	0.449	0.463	0.445	0.430	0.502	0.393	0.496	0.466
SQ2 Squeteague Harbor Annual TN means													
2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
0.538	0.458	0.477	0.483	0.371	0.399	0.552	0.518	0.455	0.373	0.521	0.514	0.439	0.410

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 Megansett Harbor estuarine system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of Megansett Harbor. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. The MEP Technical Team has utilized this model in water quality studies of other embayment systems in southeastern Massachusetts, including Pleasant Bay (Howes *et al*., 2006); New Bedford Harbor (Howes *et al*., 2008) and Sandwich Harbor (Howes *et al*., 2014).

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 MEP watershed loading analysis (with ARCgis support from the Cape Cod Commission), 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 Megansett Harbor system.

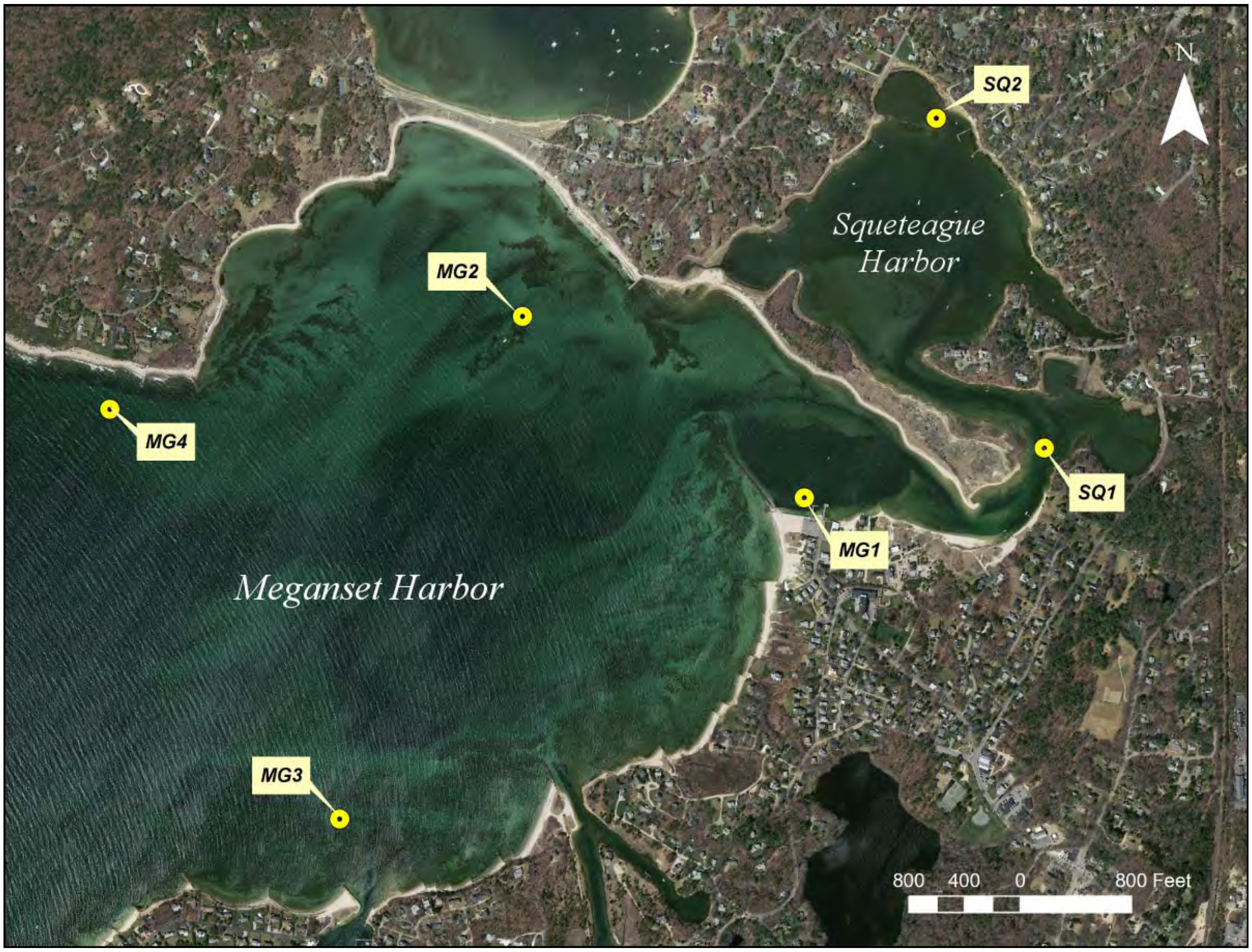


Figure VI-1. Estuarine water quality monitoring station locations in the Megansett Harbor estuary system. Station labels correspond to those provided in Table VI-1.

VI.2.1 Model Formulation

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

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

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

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

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

VI.2.2 Water Quality Model Setup

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

For each model, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 14 day (336 hour) period corresponding to the hydrodynamic model calibration. 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 Megansett Harbor model.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed and direct atmospheric deposition loads for Megansett Harbor were evenly distributed at grid cells along the perimeter of the sub-embayment. Benthic regeneration loads were distributed among all the other, non-watershed loading elements of each material type described in Chapter V .

The loadings used to model present conditions in the Megansett Harbor system are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. In the main portion off Megansett Harbor the net benthic flux is negative which indicates a net uptake of nitrogen in the bottom sediments. In the inner portions of the system, at Squeteague Harbor, the net benthic flux is positive, indicating a net nitrogen flux from the bottom sediments and into the water column.

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 at the outer boundary of Megansett Harbor was set at 0.329 mg/L, based on SMAST data at station MG4.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Megansett Harbor	18.978	5.556	-22.515
Megansett Channel	3.699	0.386	-0.682
Squeteague Harbor	9.263	1.000	0.151
System Total	31.940	6.942	-23.046

VI.2.4 Model Calibration

Calibration of the total nitrogen model of Megansett Harbor proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (*E*) values were varied through the modeled system by setting different values of *E* for each grid material type, as designated in Section V. Observed values of *E* in coast estuary areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of *E* used in each sub-embayment of the modeled system are presented in Table VI-3. These values were used to develop the “best-fit” total nitrogen model calibration. For the case of TN modeling, “best fit” can be defined as minimizing the error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

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

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

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

Embayment Division	E m^2/sec
Outer Megansett	1.0
Inner Megansett	1.0
Megansett Channel	1.0
Squeteague Harbor	1.0
Marsh plain	0.2

Also presented in Figure VI-3 are unity plot comparisons of measured data verses modeled target values for each system. The computed R^2 correlation is 0.81 and the root mean squared (rms) error of 0.023 mg/L.

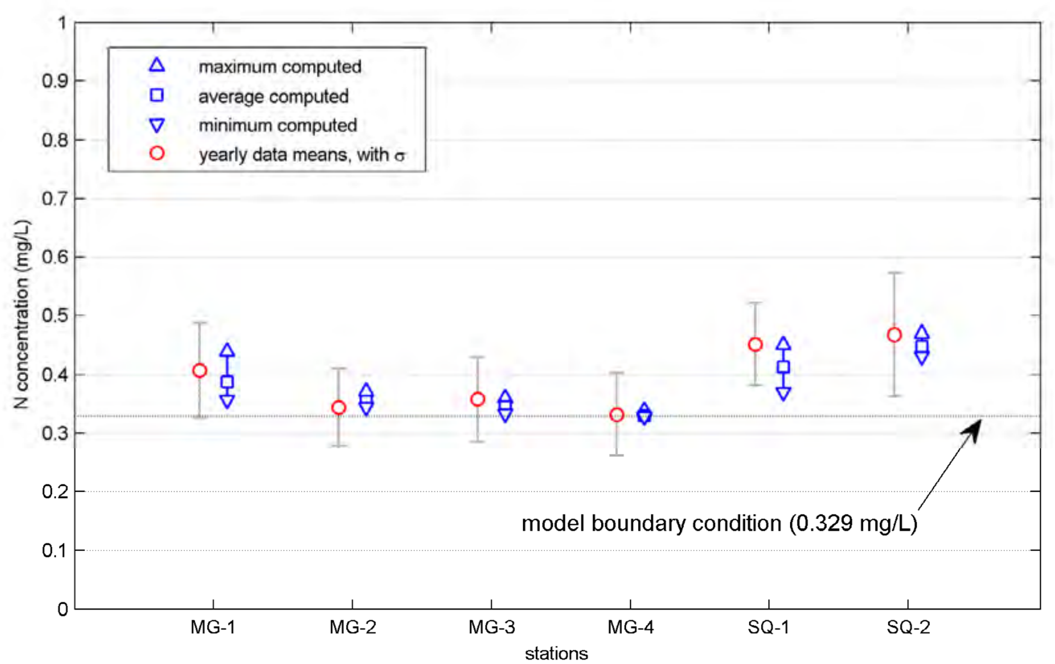


Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the of Megansett Harbor system. Station labels correspond with the MEP IDs provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during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

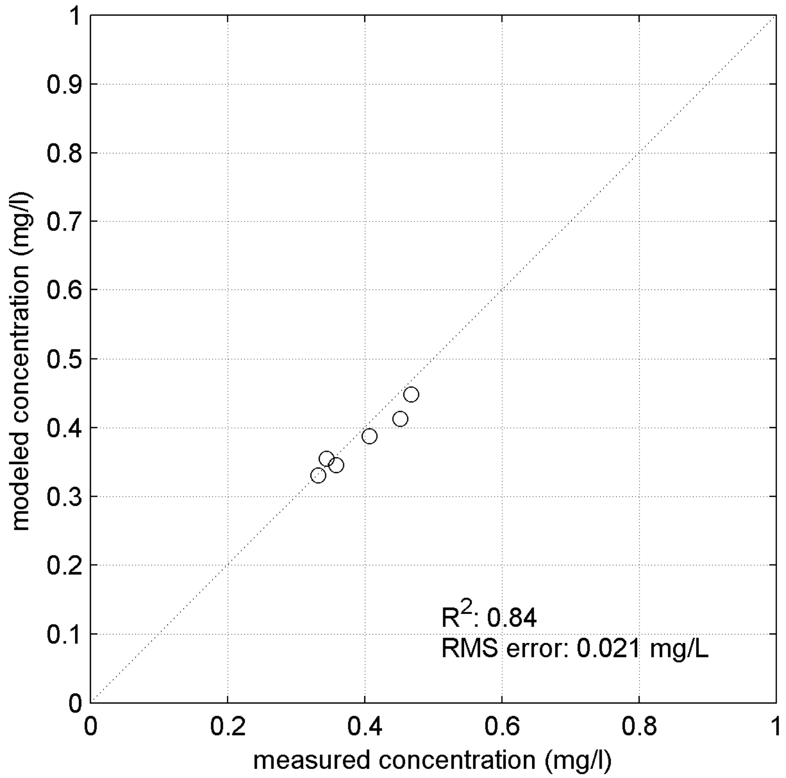


Figure VI-3. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are 0.84 and 0.021 mg/L respectively.

A contour plot of calibrated model output is shown in Figures VI-4. In this figure, color contours indicate nitrogen concentrations throughout the model domain. The output in these figures show average total nitrogen concentrations, computed using the full 14-tidal-day model simulation output period.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically corroborated by modeling salinity. This step was performed for the of Megansett Harbor system using salinity data collected at the same stations as the nitrogen data. For the salinity verification, none of the model dispersion coefficients were changed from the values used in the TN calibration. Comparisons of modeled and measured salinities are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. The RMS error of the model is 1.4 ppt.

The only required inputs into the RMA4 salinity model of the system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, rain, surface water and groundwater inputs. The open boundary salinity was set at 30.0 ppt. Freshwater input salinities were set at 0 ppt. Combined groundwater and direct rainfall to the three main system segments are 6.06 ft^3/sec (14,824 m^3/day) for outer Megansett Harbor, 1.39 ft^3/sec (3,396 m^3/day) for the inner Megansett Harbor channel, and 4.42 ft^3/sec (10,802 m^3/day) for Squeteague Harbor. Groundwater and rainfall flows were distributed evenly in the model along elements positioned along the model's land boundary.

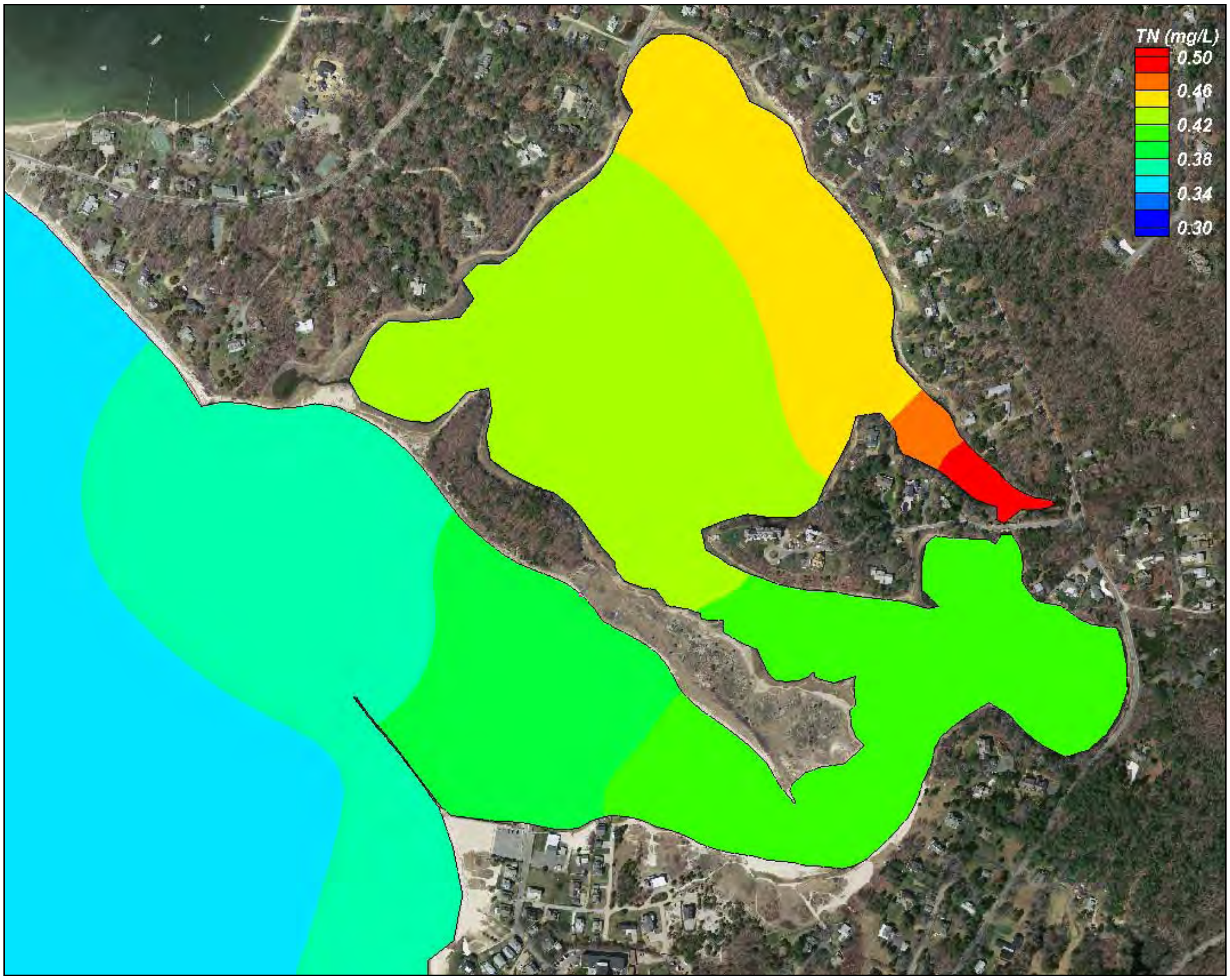


Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the of Megansett Harbor system.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

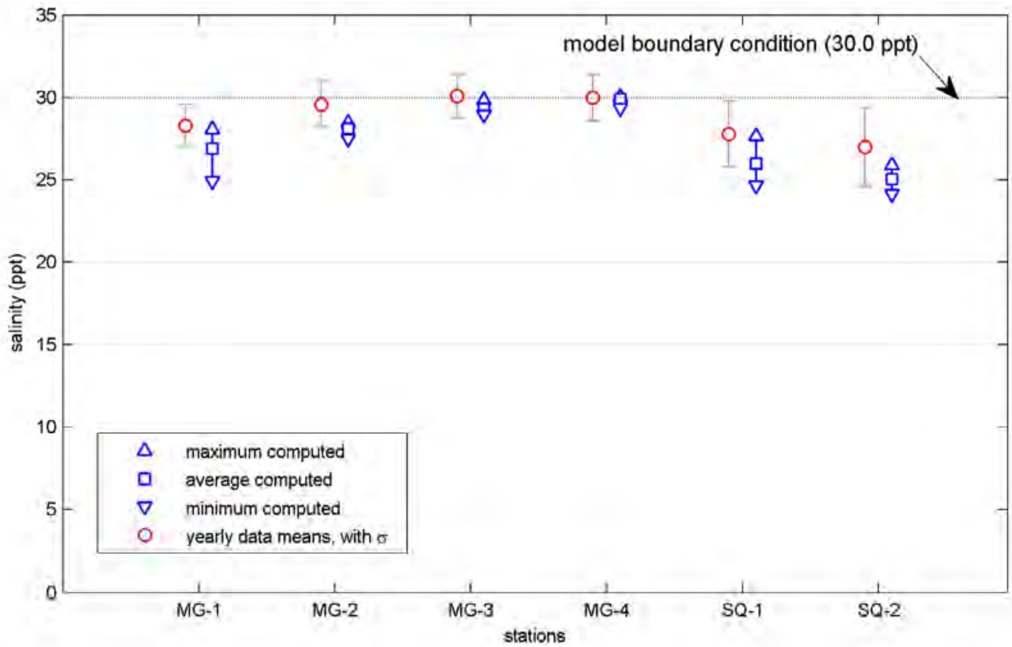


Figure VI-5. Comparison of measured and calibrated model output at stations in Megansett Harbor. Station labels correspond with those in Table VI-1. Model output is presented as a range of values from minimum to maximum computed during the simulation period (triangle markers), along with average computed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

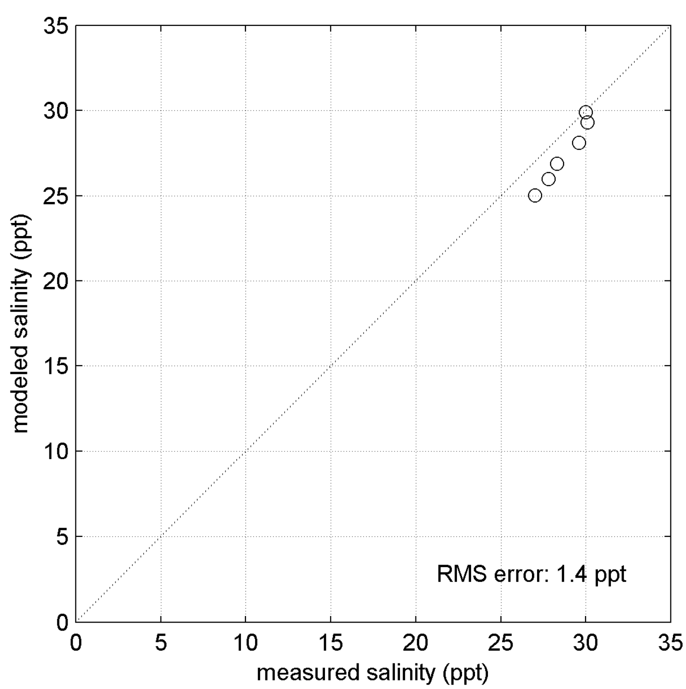


Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. RMS error for this model verification run is 1.4 ppt.

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

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

sub-embayment	present load (kg/day)	Build-out (kg/day)	build-out % change	no load (kg/day)	no load % change
Megansett Harbor	18.978	27.436	+44.6%	0.937	-95.1%
Megansett Channel	3.699	4.551	+23.0%	0.260	-93.0%
Squeteague Harbor	9.263	9.710	+4.8%	0.847	-90.9%
System Total	31.940	41.696	+30.5%	2.044	-93.6%

VI.2.6.1 Build-Out

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

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Table VI-5. **Build-out** scenario sub-embayment and surface water loads used for total nitrogen modeling of the Megansett 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)
Megansett Harbor	27.436	5.556	-24.473
Megansett Channel	4.551	0.386	-0.736
Squeteague Harbor	9.710	1.000	0.176
System Total	41.696	6.942	-25.033

Following development of the nitrogen loading estimates for the build-out scenario, the water quality models of the system was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). In this table, the percent change *P* over background presented in this table is calculated as:

$$P = (N_{scenario}-N_{present})/(N_{present}-N_{background})$$

where N is the nitrogen concentration at the indicated monitoring station for present conditions and the loading scenario (i.e., build-out in this case), and also in outer Megansett Harbor (background). Total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. For build-out, the increase in modeled TN concentrations is greater than 18% at all stations. A contour plot showing average TN concentrations throughout the Harbor system is presented in Figure VI-8 for the model of build-out loading.

Table VI-6. Comparison of model average total N concentrations from present loading and the **build-out scenario**, with percent change over background in Outer Megansett Harbor (0.329 mg/L), for the Megansett Harbor system.				
Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out (mg/L)	% change
Inner Megansett Harbor	MG1	0.387	0.406	+31.8%
Outer Megansett Harbor	MG2	0.355	0.368	+51.9%
Outer Megansett Harbor	MG3	0.346	0.353	+47.0%
Outer Megansett Harbor	MG4	0.330	0.331	+70.0%
Inner Megansett Harbor	SQ1	0.413	0.434	+24.9%
Squeteague Harbor	SQ2	0.448	0.471	+18.9%

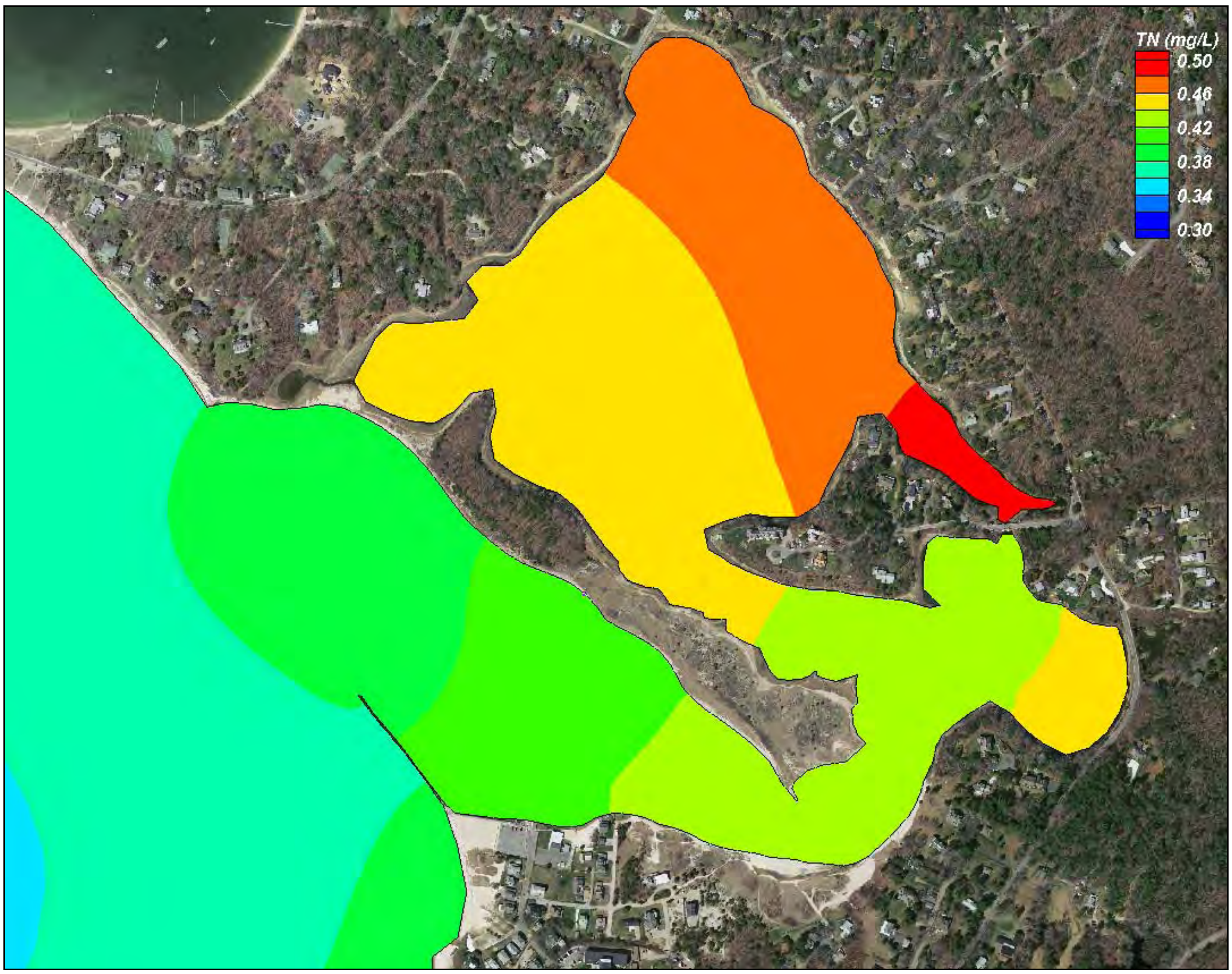


Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Megansett Harbor system, for projected build-out scenario loading conditions.

VI.2.6.2 No Anthropogenic Load

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

Table VI-7. "**No anthropogenic loading**" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Megansett 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)
Megansett Harbor	0.937	5.556	-16.838
Megansett Channel	0.260	0.386	-0.491
Squeteague Harbor	0.847	1.000	0.076
System Total	2.044	6.942	-17.253

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations at each monitoring station. Again, total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was large, with all areas of the system experiencing reductions greater than 100%, compared to the background concentration of 0.329 in the outer harbor. TN concentrations drop below background in Buzzards Bay due to the projected large negative benthic flux of harbor sediments. A contour plot showing TN concentrations throughout the system is shown pictorially in Figure VI-9.

Table VI-8. Comparison of model average total N concentrations from present loading and the "**No anthropogenic loading**" ("no load"), with percent change over background in Outer Megansett Harbor (0.329 mg/L), for the Megansett Harbor system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	No-load (mg/L)	% change
Inner Megansett Harbor	MG1	0.387	0.302	-146.7%
Outer Megansett Harbor	MG2	0.355	0.308	-183.3%
Outer Megansett Harbor	MG3	0.346	0.324	-131.9%
Outer Megansett Harbor	MG4	0.330	0.328	-200.0%
Inner Megansett Harbor	SQ1	0.413	0.296	-139.1%
Squeteague Harbor	SQ2	0.448	0.284	-137.9%

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

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, total pigment (chlorophyll-a + pheophytin), and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Megansett Harbor and Squeteague Harbor embayment system in the Towns of Falmouth and Bourne, MA, our assessment is based upon data from the water quality monitoring database (2000-2013) developed by the Buzzards Bay Coalition, surveys of eelgrass distribution (1951, 1995, 2001, 2012), benthic animal communities (fall 2005, 2014), sediment characteristics (summer 2005, 2014), and dissolved oxygen records (summer 2005, 2006). 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 this system (Section VIII). It should be noted that nitrogen enrichment occurs through 2 primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with the low nitrogen waters of Buzzards Bay. Megansett Harbor and Squeteague Harbor have increasing nitrogen loading from the associated watersheds from shifting land-uses and Squeteague Harbor periodically may become partially restricted due to sediment deposition. Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs.

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen threshold determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and total pigment (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 (YSI 6600) in both Megansett Harbor and Squeteague Harbor at locations that would be representative of the dissolved oxygen conditions at critical locations in each of the systems. Sensors (6) were deployed to capture oxygen conditions within Megansett Harbor (3 in outer harbor) and Squeteague Harbor (3, 2 in basin furthest removed from the influence of inflowing waters from Buzzards Bay and 1 in the region of the Squeteague inlet). The dissolved oxygen and total pigment (chlorophyll-a + pheophytin) moorings were deployed to record the frequency and duration of low oxygen conditions and phytoplankton dynamics 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 both the Megansett Harbor and Squeteague Harbor systems 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 while Megansett Harbor still retains eelgrass habitat, Squeteague Harbor does not presently. Extensive eelgrass habitat is still present in Megansett Harbor, although there is some evidence of recent declines in some areas. In contrast, in Squeteague Harbor it should be noted that although some potential eelgrass habitat was identified in the 1951 aerial photographs, it was not able to be confirmed and without verification or correlative data, this potential patch in the 1951 photo analysis is not sufficient to drive nitrogen threshold analysis. As such, eelgrass habitat was used as an indicator in the MEP assessment for Megansett Harbor and benthic infauna habitat for Squeteague Harbor.

Analysis of inorganic N/P molar ratios within the watercolumn of Megansett Harbor and Squeteague Harbor supports the contention that nitrogen is the nutrient to be managed, as the ratio in Megansett Harbor (2.4) and Squeteague Harbor (3.5) is clearly below the Redfield Ratio value (16) indicating that nitrogen additions will increase phytoplankton production in these systems. Within the Megansett/Squeteague Harbor Estuary, since temporal changes in eelgrass distribution could provide a basis for evaluating nutrient related habitat quality, nutrient threshold determination was based on the history of eelgrass distribution as well as results from the dissolved oxygen and total pigment (chlorophyll-a + pheophytin) mooring and water quality monitoring data, macroalgae surveys, and the benthic infaunal community characterization.

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

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 4 mg L^{-1}. Massachusetts State Water Quality Classification indicates that SA (high quality) waters be able to maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Megansett Harbor and Squeteague Harbor embayment are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality and that it is the designated water quality that is the target of 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'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-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the bottom of the embayment within key regions of the Megansett Harbor and Squeteague Harbor system (Figure VII-2). 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 25-42 days within the interval from mid-June through early-September. All of the mooring data from the Megansett Harbor and Squeteague Harbor embayment system were collected during the summer of 2005 with the exception of the Squeteague Inner mooring which failed in 2005 and was redeployed in the summer of 2006 and the Megansett 2 mooring deployed in 2006.

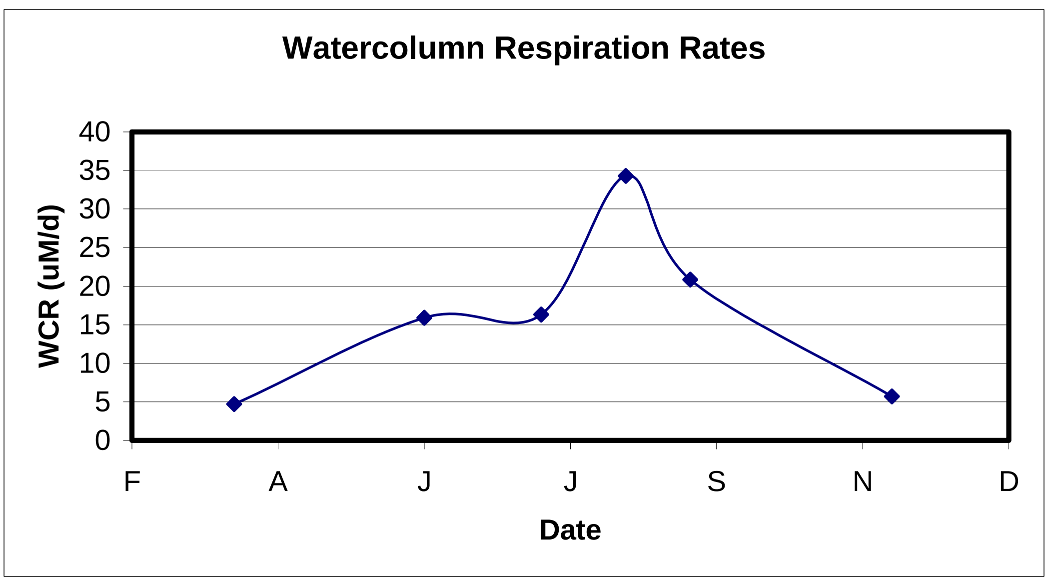


Figure VII-1. Example of typical average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System, Cape Cod (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

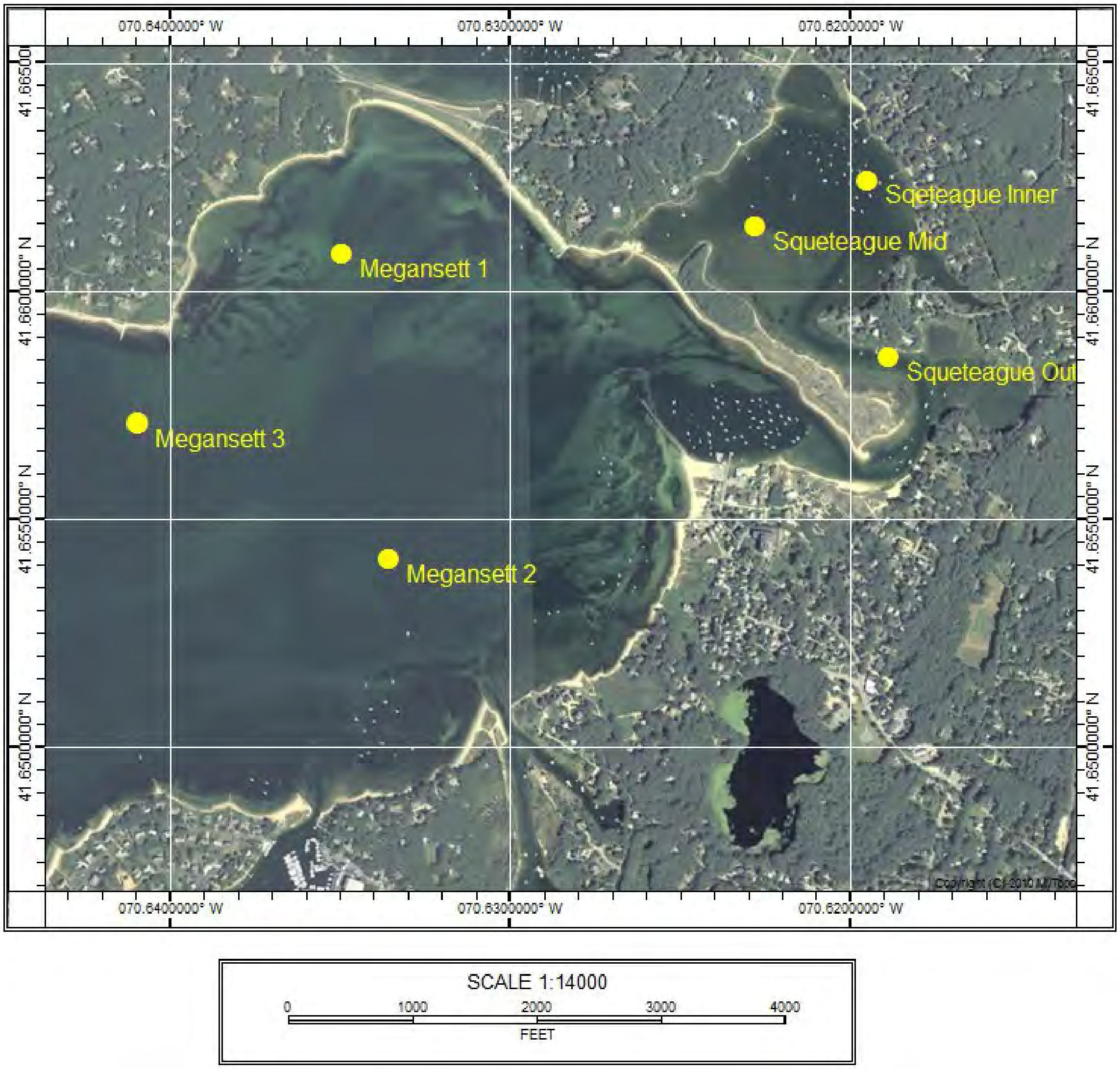


Figure VII-2. Aerial Photograph of the Megansett Harbor and Squeteague Harbor embayment system in the Towns of Falmouth and Bourne showing the location of the continuously recording dissolved oxygen / total pigment (chlorophyll-a + pheophytin) sensors deployed during the Summer of 2005 and 2006.

Similar to other embayments in southeastern Massachusetts, the Megansett Harbor and Squeteague 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 total pigment (chlorophyll-*a* + pheophytin) records were examined both for temporal trends and to determine the percent of the 25 day to 42 day deployment periods 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 total pigment (chlorophyll-*a* + pheophytin) levels indicate moderately nutrient enriched waters within the Megansett Harbor basin landward of the rock jetty and the inner basin of Squeteague Harbor. The dissolved oxygen and total pigment data is further described below and depicted in Figures VII-3 through VII-14. The oxygen data is consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of total pigment, particularly in Squeteague Harbor. The measured levels of oxygen depletion and enhanced total pigment levels follows the spatial pattern of total nitrogen levels in this system (Section VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of the Megansett Harbor and Squeteague Harbor estuarine system.

The oxygen record for both Megansett Harbor and Squeteague Harbor show levels of oxygen depletion and daily oxygen excursions and total pigment levels indicative of varying levels of nitrogen enrichment. Oxygen records from both basins coupled with the multi-year monitoring by BayWatchers indicate that oxygen levels are generally lower than atmospheric equilibration but only infrequently decline to <4 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). In the present analysis, the oxygen levels generally do not significantly exceed equilibrium but do show some depletion at some sites. Only the Squeteague mid mooring shows moderate elevation in daytime oxygen and some depletion to 4 mg/L at night, while all sites periodically show oxygen levels below equilibrium indicating elevated organic matter stemming from moderate nitrogen enrichment. The clear evidence of periodic low to moderate oxygen depletion indicates that portions of both the Megansett Harbor and the Squeteague Harbor system are at or slightly above their nitrogen thresholds with potential stress to benthic animal communities. The embayment specific results are as follows:

Megansett Harbor 1 DO/CHLA Mooring (Figures VII-3 and VII-4):

Three moorings were deployed in the outer Megansett Harbor main basin of the overall estuarine system. One of the three instrument moorings (Megansett Harbor 1) was located in the northern section of the main basin that constitutes Megansett Harbor (Figure VII-2). The Megansett Harbor 1 mooring is located in the nearshore adjacent eelgrass beds and is still removed from the inlet connecting the Megansett Harbor basin to the Squeteague Harbor basin and influence of higher nutrient water coming from the innermost portion of the estuary. The Megansett Harbor 1 mooring in the northern section of the main basin was centrally located and approximately 1,200 meters from where the inlet connects Megansett Harbor to Squeteague Harbor. Moderate daily excursions in oxygen levels were observed at this location, ranging from levels at or just above air equilibration declining briefly to 4-5 mg L^{-1} (Figure VII-3, Table VII-1). Oxygen levels that drop below 4 mg L^{-1} are indicative of potential oxygen stress but that occurred only once during the deployment period. Oxygen in bottom water was found to be >5 mg L^{-1}, 95% of the record and was >6 mg L^{-1} in 97% of the BayWatcher grab samples (N=37). The low organic enrichment of the system is also demonstrated by the general lack of algal blooms with the exception of 1 bloom observed during the later part of the meter deployment period (first week of September). That bloom corresponded to higher rates of photosynthesis (carbon fixation) and larger oxygen excursions and rapid declines in oxygen after sunset stemming from respiration. However, on average chlorophyll-a levels were 7.0 ug L^{-1} and 5.4 ug L^{-1} in the long-term record (BayWatcher grab samples, N=52).

Oxygen levels regularly persisted between 5 and 6 mg L^{-1} and periodically exceeded 8 mg L^{-1}. These oxygen levels indicate a system generally in balance. Over the 42 day deployment there was one moderately intense phytoplankton bloom where total pigment increased to 10-20 ug L^{-1} with a short period of bloom activity where total pigment concentrations peaked at over 40 ug L^{-1}. The generally moderate to high levels of oxygen observed in this system is indicative of a system at or just beyond its ability to assimilate nitrogen without impairment, which is also consistent with the generally low total pigment levels In this portion of the main basin of Megansett Harbor, total pigment exceeded the 10 ug L^{-1} benchmark 14 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. Both the time-series and grab sample data at this mooring location are relatively low for southeastern Massachusetts estuaries in summer and indicate a system only slightly to moderately nitrogen enriched.

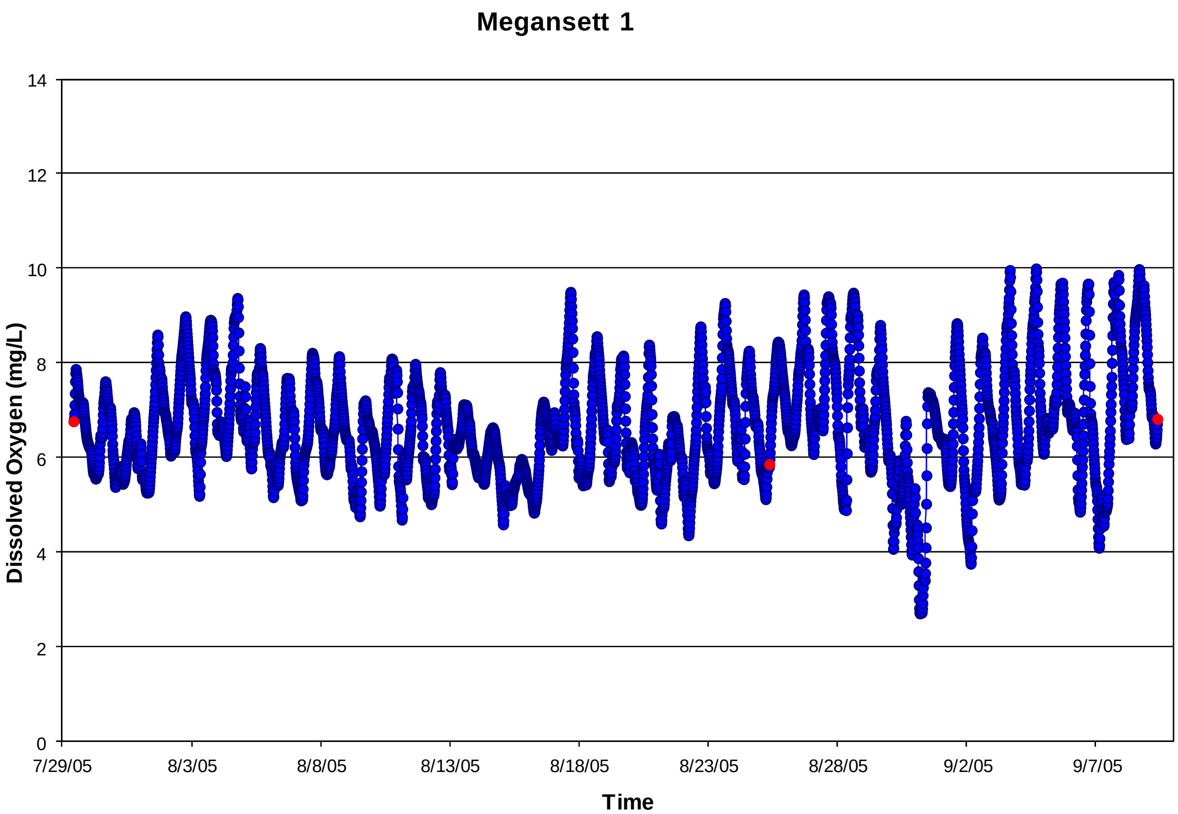


Figure VII-3. Bottom water record of dissolved oxygen at the Megansett Harbor 1 station, Summer 2005. Calibration samples represented as red dots.

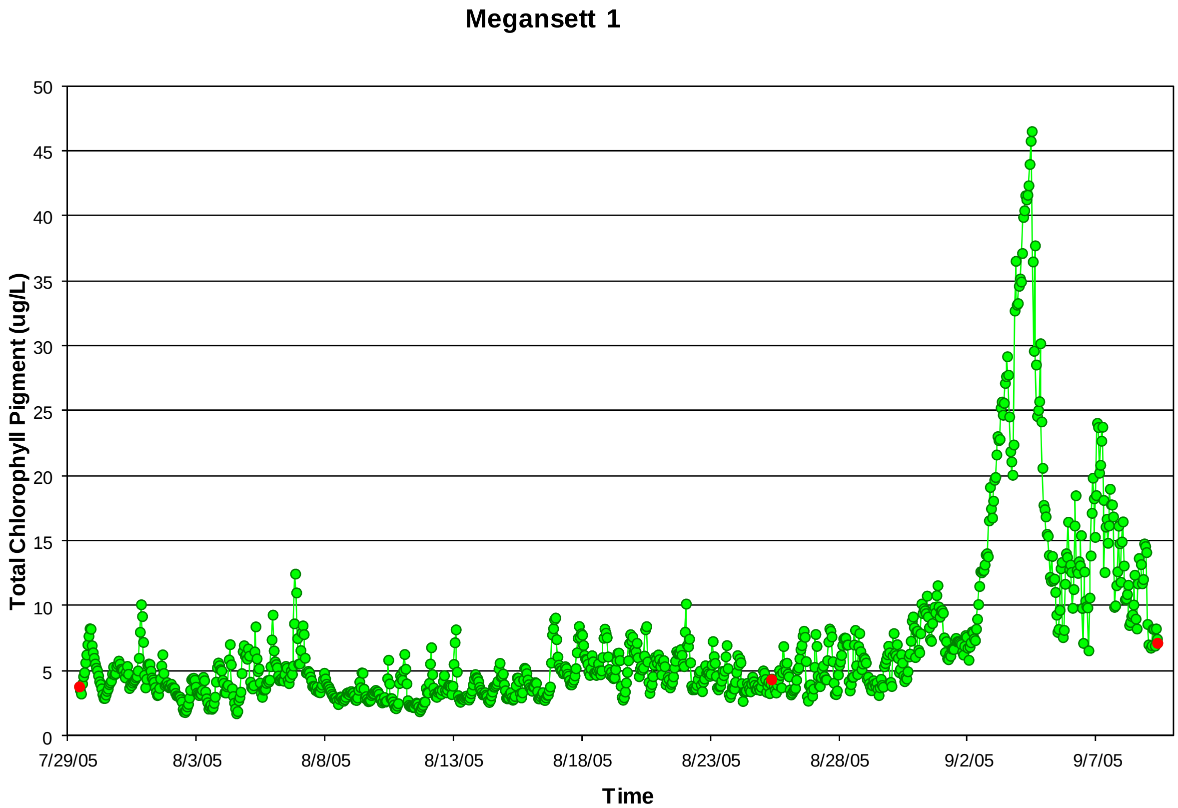


Figure VII-4. Bottom water record of Total pigment at the Megansett Harbor 1 station, Summer 2005. Calibration samples represented as red dots.

Megansett Harbor 2 DO/CHLA Mooring (Figures VII-5 and VII-6):

The second of the three instrument moorings (Megansett Harbor 2) was located within the deep central basin (southern edge) of Megansett Harbor offshore from Rands Harbor (Figure VII-2). The Megansett Harbor 2 mooring is located more centrally and to the south of the other two Megansett Harbor moorings (1,3), and is potentially affected by the discharges from Fiddlers Cove and Rands Harbor and influence of higher nutrient water coming from those innermost portions of the overall estuary. The Megansett Harbor 2 mooring in the deeper waters of the main basin was located approximately 1,000 meters from where the inlet connects Megansett Harbor to Squeteague Harbor and 600 meters from where Rands Harbor and Fiddlers Cove discharge to Megansett Harbor on ebbing tides. Low to moderate daily excursions in oxygen levels were observed at this location, but overall oxygen levels periodically declined to 2-4 mg L^{-1} (Figure VII-5, Table VII-1). Instantaneous oxygen levels that frequently drop to 2-4 mg L^{-1} are indicative of oxygen stress. It appears likely that some of the oxygen depletion at this site is due to the structure of the basin, where organic matter deposition occurs in the deep water off shore of the eelgrass beds in the shallows and outflows from Fiddlers Cove and Rands Harbor. The low oxygen does not appear to be related to nitrogen or chlorophyll-a levels (6.3 ug L^{-1} long-term record from BayWatchers) or particulate carbon concentrations (0.102 mg L^{-1}) which are low for estuarine waters in southeastern Massachusetts. It is likely that the low oxygen in the "hole" is the result of the region being a "particle trap" like the 3 deep basins in Nantucket Harbor. These Nantucket Harbor basins were observed to collect organic matter and macrophyte detritus (macroalgae and eelgrass) from the adjacent shallows. The low oxygen events were also not related to phytoplankton blooms or high levels or to high particulate levels in the watercolumn, as also seen at the mooring 2 site in Megansett Harbor. Accumulation of macrophyte detritus was confirmed by diver observations (S. Aubrey personal communication).

Oxygen levels regularly persisted between 4 and 6 mg L^{-1} and occasionally exceeded 7 mg L^{-1}. These moderate oxygen levels are primarily the result of respiration in bottom waters due to organic matter deposition and reduced ventilation due to basin depth. Over the 39 day deployment there appear to be three low intensity phytoplankton blooms where total pigment increased to 10-15 ug L^{-1} with a short period of bloom activity where total pigment concentrations peaked at just over 15 ug L^{-1}. The lower oxygen levels compared to the other two mooring locations in Megansett Harbor are inconsistent with the generally low total pigment levels in this portion of Megansett Harbor (average total pigment by mooring, 5.3 ug L^{-1}). In this portion of the main basin of Megansett Harbor, total pigment exceeded the 10 ug L^{-1} benchmark only 7 percent of the time (Table VII-2, Figure VII-8). Average chlorophyll levels over 10 ug L^{-1} have been used to indicate eutrophic conditions in embayments.

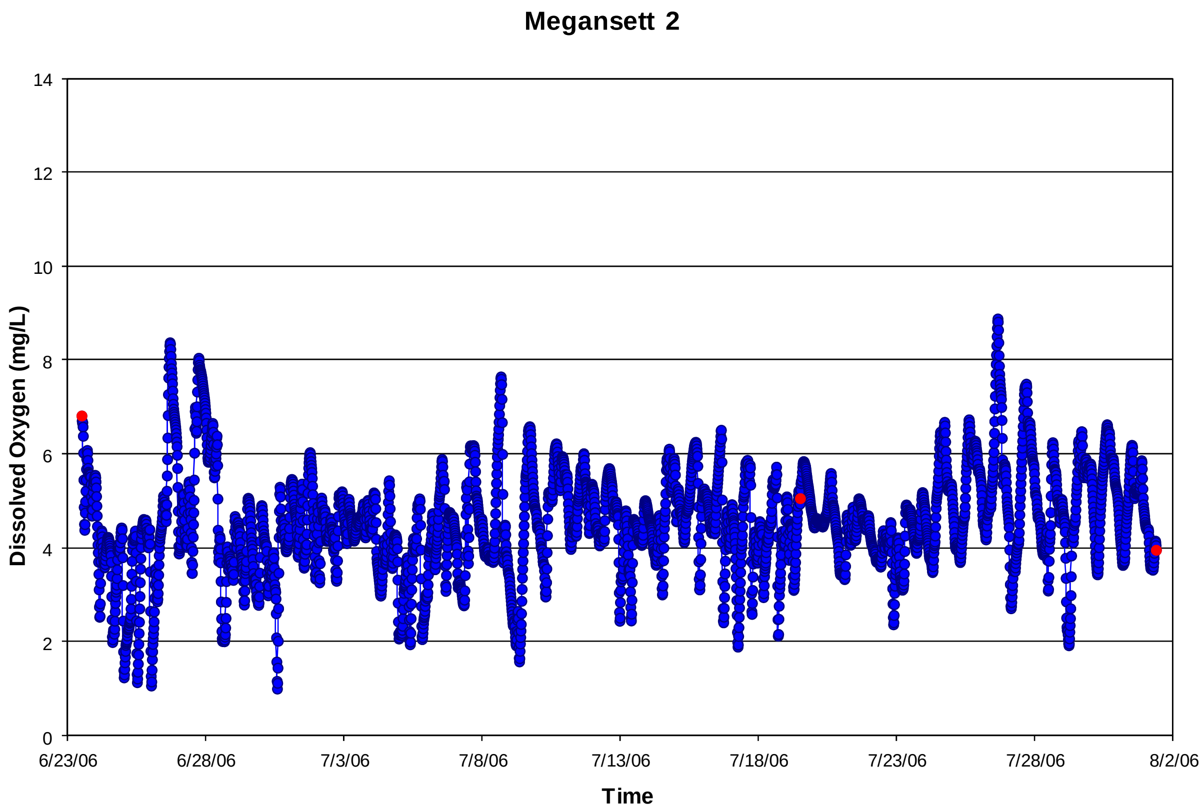


Figure VII-5. Bottom water record of dissolved oxygen at the Megansett Harbor 2 station, Summer 2006. Calibration samples represented as red dots.

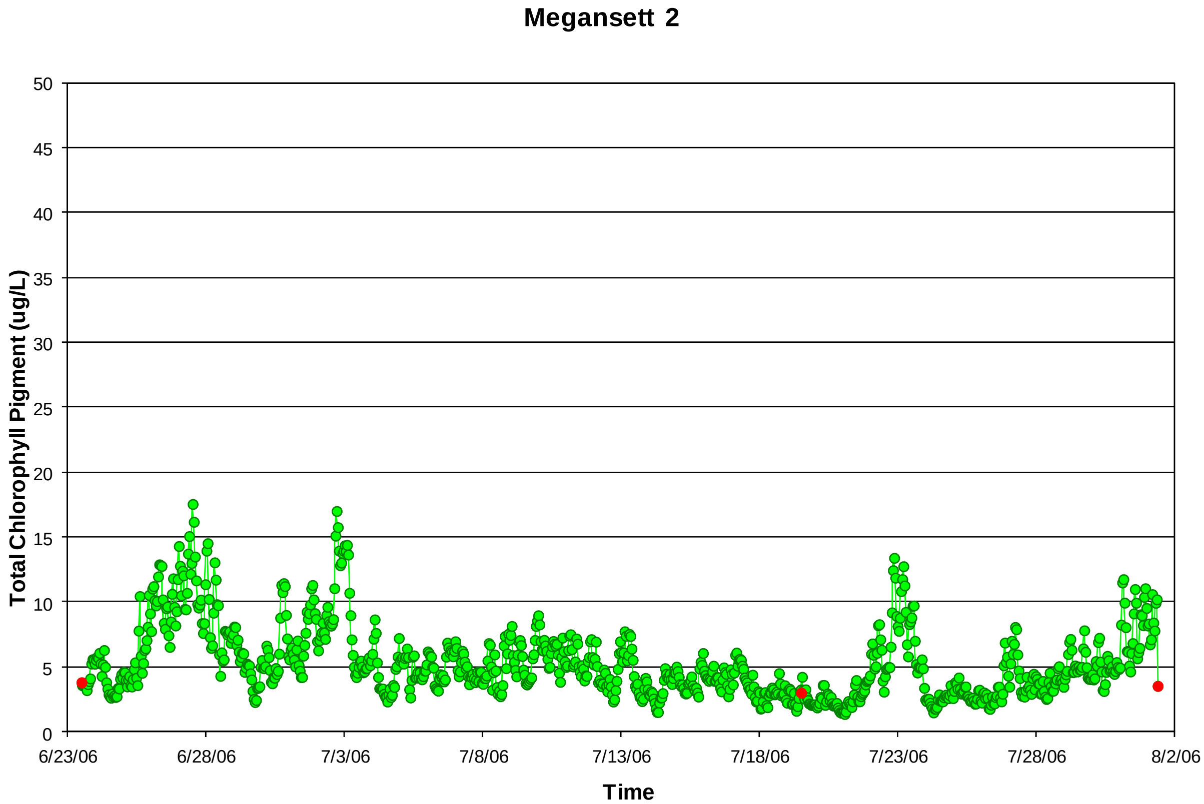


Figure VII-6. Bottom water record of Total pigment in the Megansett Harbor 2 station, Summer 2006. Calibration samples represented as red dots.

Megansett Harbor 3 DO/CHLA Mooring (Figures VII-7 and VII-8):

The third of the three instrument moorings (Megansett Harbor 3) was located in the outermost section of the main basin that constitutes Megansett Harbor (Figure VII-2). The Megansett Harbor 3 mooring is located offshore in more open water than the two other Megansett Harbor moorings and is well removed from the inlet connecting the Megansett Harbor basin to the Squeteague Harbor basin as well as the discharges from Fiddlers Cove and Rands Harbor and influence of higher nutrient water discharging along the southern shore of the Harbor. The Megansett Harbor 3 mooring in the outermost section of the main basin was located approximately 1,500 meters from where the inlet connects Megansett Harbor to Squeteague Harbor and 1,200 meters from where Rands harbor discharges to Megansett Harbor. Relatively low daily excursions (~2 mg L^{-1}) in oxygen levels were observed at this location, with few excursion above air equilibration and bottom water oxygen above 4 mg L^{-1} (Figure VII-7, Table VII-1). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of potential oxygen stress. The oxygen levels and excursions were typical of relatively low organic enrichment, consistent with the general lack of algal blooms. Only a single small bloom to ~10 ug L^{-1} was observed, with average total pigment (chlorophyll-a + pheophytin) levels of 4.7 ug L^{-1} for the deployment period (MG-4 BayWatcher 5.1 ug L^{-1}, N=52).

Oxygen levels regularly persisted between 5 and 7 mg L^{-1} and occasionally exceeded 8 mg L^{-1}. These moderate oxygen levels are primarily the result of respiration by low to moderate phytoplankton biomass and relatively quiescent waters. Over the 42 day deployment there appear to be one low intensity phytoplankton blooms where total pigment increased to ~10 ug L^{-1}. The low frequency of oxygen depletion observed in this system is indicative of low habitat impairment which is also consistent with the generally low total pigment levels, also indicative of low nitrogen enrichment in this portion of Megansett Harbor. In this portion of the main basin of Megansett Harbor, total pigment exceeded the 10 ug L^{-1} benchmark only 8 percent of the time (Table VII-2, Figure VII-8) and conditions were consistent with the open water nature of the basin and its free exchange with high quality Buzzards Bay waters. Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

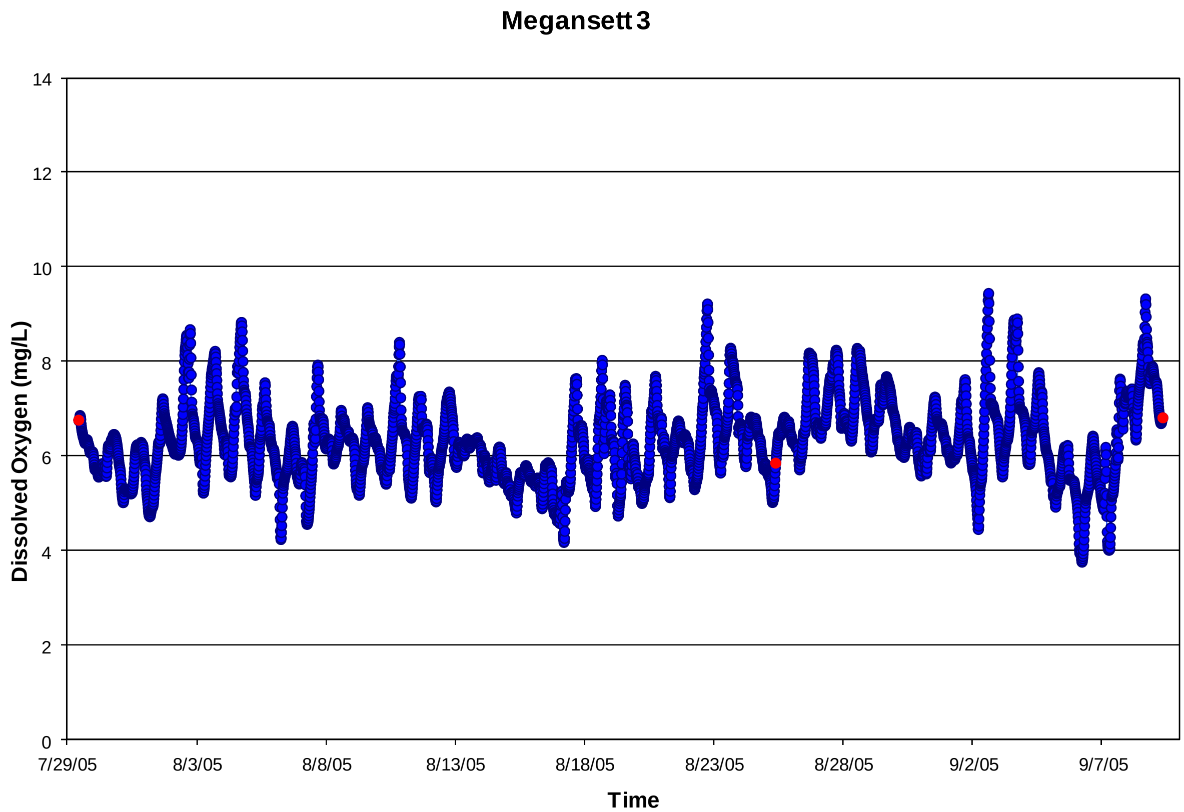


Figure VII-7. Bottom water record of dissolved oxygen at the Megansett Harbor 3 station, Summer 2005. Calibration samples represented as red dots.

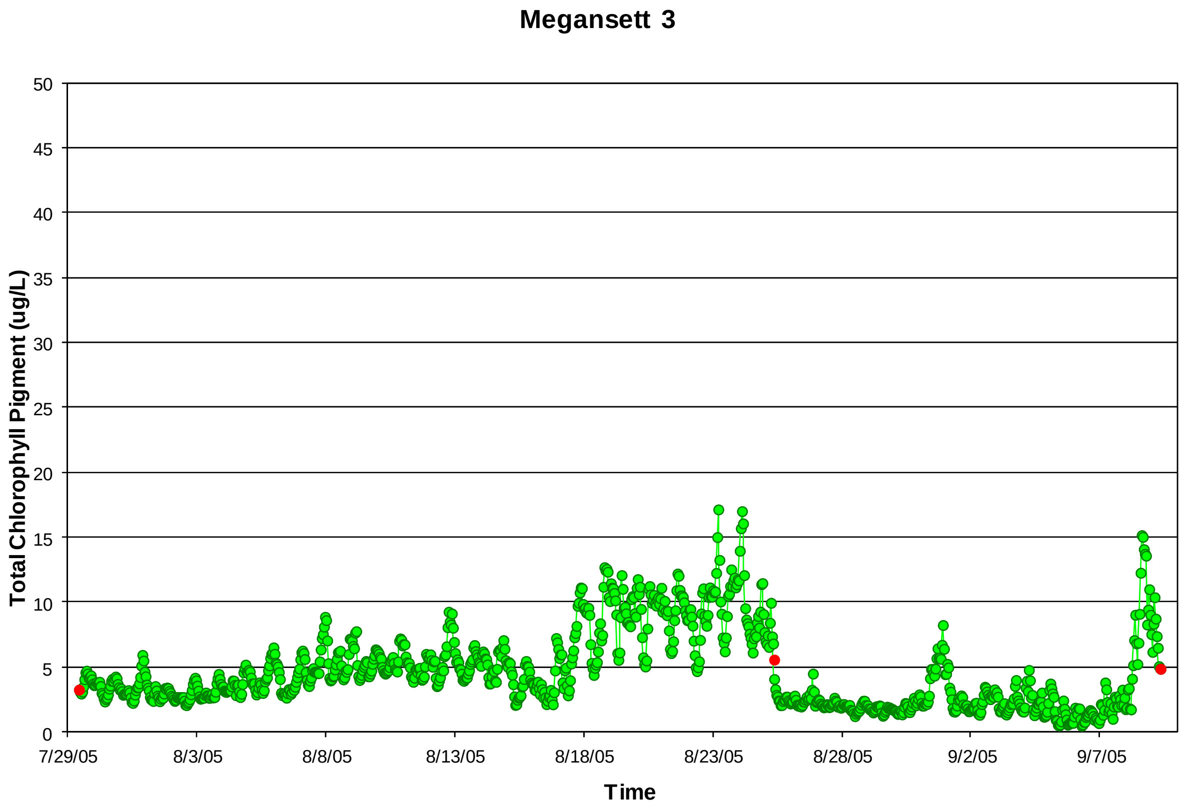


Figure VII-8. Bottom water record of Total pigment in the Megansett Harbor 3 station, Summer 2005. Calibration samples represented as red dots.

Squeteague Harbor Inner DO/CHLA Mooring (Figures VII-9 and VII-10):

As in Megansett Harbor, three moorings were deployed in the main basin of Squeteague Harbor portion of the overall estuarine system. One of the three instrument moorings (Squeteague Inner) was located in the eastern section of the main basin that constitutes Squeteague Harbor (Figure VII-2). The Squeteague Inner mooring is located more in shore of the two other Squeteague Harbor moorings and is furthest removed from the inlet connecting the Megansett Harbor basin to the Squeteague Harbor basin and influence of lower nutrient water coming from Megansett Harbor / Buzzards Bay. The Squeteague Inner mooring in the northern main basin was located to one side of the harbor and approximately 1,350 meters from where the inlet connects Megansett Harbor to Squeteague Harbor. Relatively small daily excursions in oxygen levels were observed at this location, ranging from levels at or just above air equilibration to slightly less than 5 mg L^{-1} (Figure VII-9, Table VII-1). Oxygen levels that drop below 4 mg L^{-1} are indicative of potential oxygen stress and that did not occur during the deployment period. Moderate organic enrichment was observed in both the fine grained organic sediments and the elevated total pigment levels associated with a prolonged phytoplankton bloom that took place during the first three weeks (June into July) of the meter deployment period with total pigment in the 10-15 ug L^{-1} during the bloom. Similarly, long-term water quality monitoring indicates levels of 9.8 and 10.8 ug L^{-1} were typical of summer conditions (averages of SQ1 and SQ2, respectively). At the inner Squeteague mooring site, oxygen levels regularly persisted between 5 and 7 mg L^{-1} and periodically reached 8 mg L^{-1}. These moderately high oxygen levels are primarily the result of photosynthesis and ventilation from vertical mixing of the shallow water column. The periodic low levels of oxygen observed at this site is indicative of possible habitat impairment which is also consistent with the moderately high total pigment levels, also indicative of moderate nitrogen enrichment in this portion of Squeteague Harbor (average total pigment by mooring, 11.6 ug L^{-1}). In this portion of the main basin of Squeteague Harbor, total pigment exceeded the 10 ug L^{-1} benchmark 58 percent of the time (Table VII-2, Figure VII-10). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

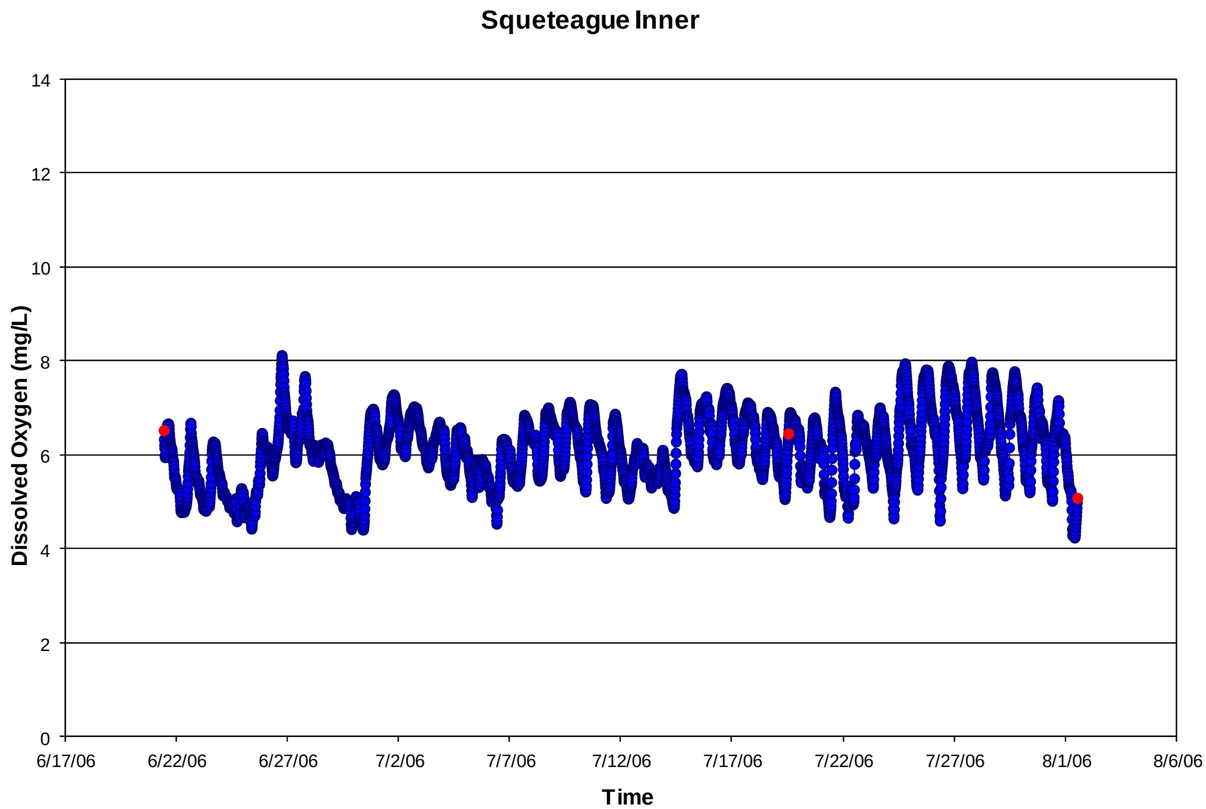


Figure VII-9. Bottom water record of dissolved oxygen at the Squeteague Harbor Inner station, Summer 2006. Calibration samples represented as red dots.

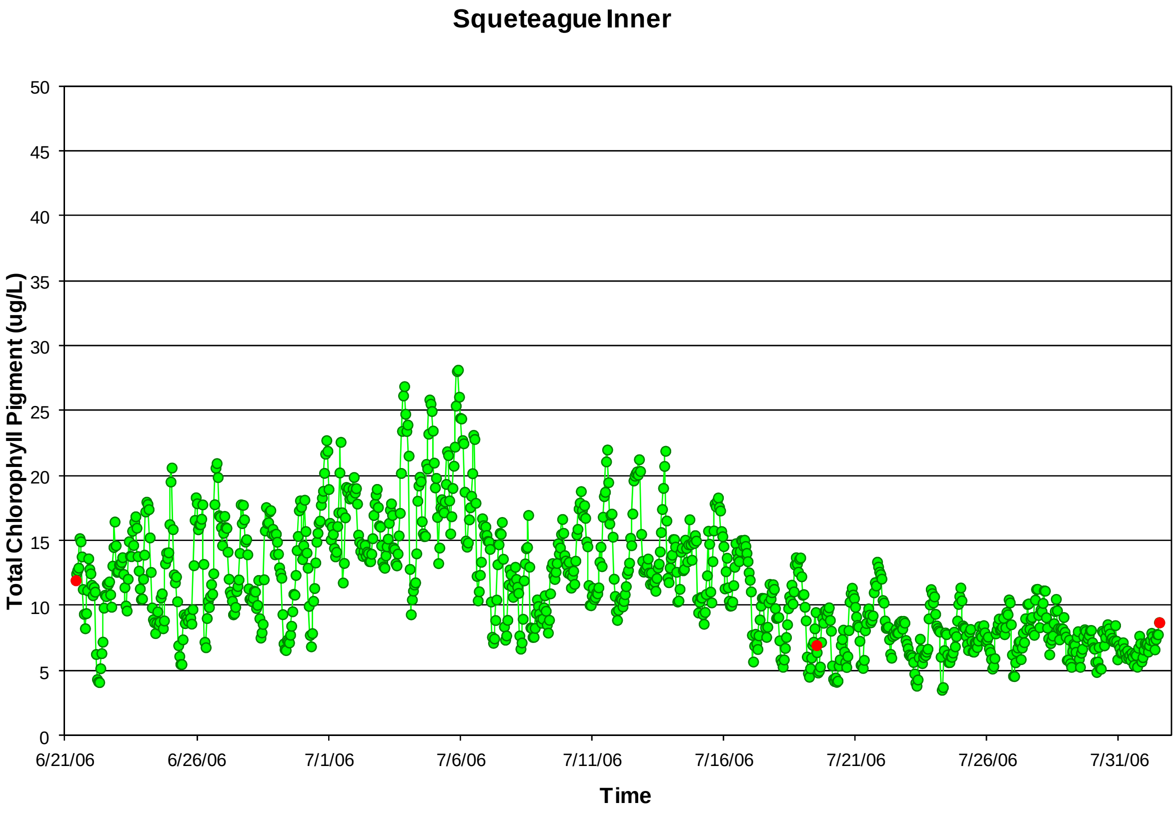


Figure VII-10. Bottom water record of Total pigment at the Squeteague Harbor Inner station, Summer 2006. Calibration samples represented as red dots.

Squeteague Harbor Mid DO/CHLA Mooring (Figures VII-11 and VII-12):

The second of the three instrument moorings (Squeteague mid) was located in the western section of the main basin that constitutes Squeteague Harbor (Figure VII-2). The Squeteague mid mooring is located more towards the barrier beach separating Megansett Harbor from Squeteague Harbor. The Squeteague Harbor mid mooring is also well distanced from the inlet connecting the Megansett Harbor basin to the Squeteague Harbor basin and influence of lower nutrient water coming from Megansett Harbor / Buzzards Bay. The Squeteague mid mooring was located approximately 1,200 meters from where the inlet connects Megansett Harbor to Squeteague Harbor. Moderate daily excursions in oxygen levels (~4 mg L^{-1}) were observed at this location, ranging from levels at or just above air equilibration to 5 mg L^{-1} and very occasionally to 4 mg L^{-1} (Figure VII-11, Table VII-1). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of potential oxygen stress and that did not occur during the deployment period. The moderate organic enrichment of the system is also demonstrated by the elevated total pigment (chlorophyll-a + pheophytin) levels associated with an observed algal bloom that took place during the first ten days (July) of the deployment period. That bloom corresponded to higher rates of photosynthesis (carbon fixation) and dark respiration from the increased biomass resulting in the observed oxygen excursions from day to night.

Oxygen levels regularly persisted between 6 and 10 mg L^{-1} with few low oxygen periods (4-5 mg L^{-1}). Over the 26 day deployment there appears to be one moderately intense phytoplankton bloom where total pigment increased to 15-20 ug L^{-1} with a short period of bloom activity where total pigment concentrations were 25-30 ug L^{-1}. The generally high oxygen levels of >6 mg L^{-1} 95% of the record do not indicate stress or likely benthic animal habitat impairment which is also consistent with the nitrogen (0.45 mg L^{-1}, tidally averaged) and total pigment levels in line with moderate nitrogen enrichment in this portion of Squeteague Harbor (average total pigment, 11.2 ug L^{-1}). In this portion of the main basin of Squeteague Harbor, total pigment exceeded the 10 ug L^{-1} benchmark 43 percent of the time (Table VII-2, Figure VII-12). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

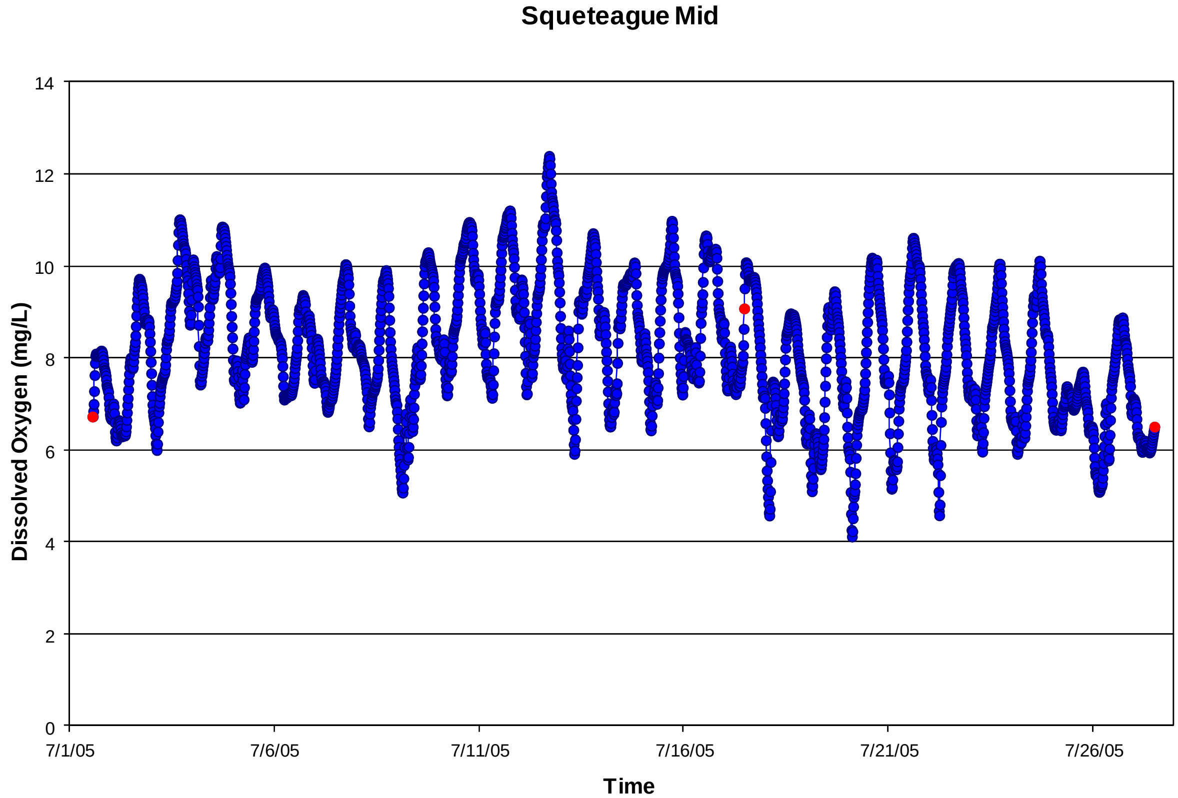


Figure VII-11. Bottom water record of dissolved oxygen at the Squeteague Harbor Mid station, Summer 2005. Calibration samples represented as red dots.

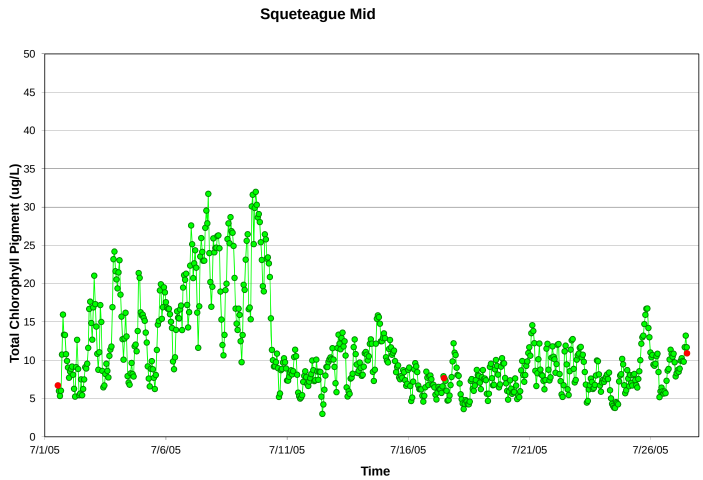


Figure VII-12. Bottom water record of Total pigment at the Squeteague Harbor Mid station, Summer 2005. Calibration samples represented as red dots.

Squeteague Harbor Outer DO/CHLA Mooring (Figures VII-13 and VII-14):

The third of the three instrument moorings (Squeteague outer) was located in the channel that connects the main basin of Squeteague Harbor with the inlet that opens to Megansett Harbor (Figure VII-2). The Squeteague outer mooring was centrally located within the channel approximately mid way between the main basin and the inlet. The Squeteague Harbor outer mooring was situated approximately 600 meters from the throat of the inlet. Moderate daily excursions (~3 mg L^{-1}) in oxygen levels were observed at this location, with oxygen ranging from just above air equilibration to 4-5 mg L^{-1} with levels rarely reaching 4 mg L^{-1} (Figure VII-11, Table VII-1). Oxygen remained above 5 mg L^{-1} 92% of the record. Oxygen levels that drop below 4 mg L^{-1} are indicative of potential oxygen stress and that was approached only once during the deployment period. The moderate organic enrichment of the system is also demonstrated by the elevated total pigment levels associated with two observed algal blooms that took place during the second and fourth weeks (July) of the meter deployment period. That bloom corresponded to higher rates of photosynthesis (carbon fixation) and larger oxygen excursions and rapid declines in oxygen after sunset stemming from respiration.

Oxygen levels regularly persisted between 5 and 8 mg L^{-1}. These moderately high oxygen levels are primarily the result of photosynthesis by phytoplankton and ventilation of bottom waters by vertical mixing of the shallow water column. Over the 26 day deployment there appears to be relatively constant phytoplankton biomass in the watercolumn averaging

11.8 ug L^{-1} with periods of 15-20 ug L^{-1} and peaks to just over 25 ug L^{-1}. The generally high oxygen observed in this system with declines approaching only 4 mg L^{-1} is indicative of low stress to benthic animal communities and is consistent with the moderate total pigment levels, stemming from the moderate nitrogen enrichment (TN <0.5 mg L^{-1}) in this portion of Squeteague Harbor (average total pigment by mooring, 11.8 ug L^{-1}). In this portion of the main basin of Squeteague Harbor, total pigment exceeded the 10 ug L^{-1} benchmark 57 percent of the time (Table VII-2, Figure VII-12). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

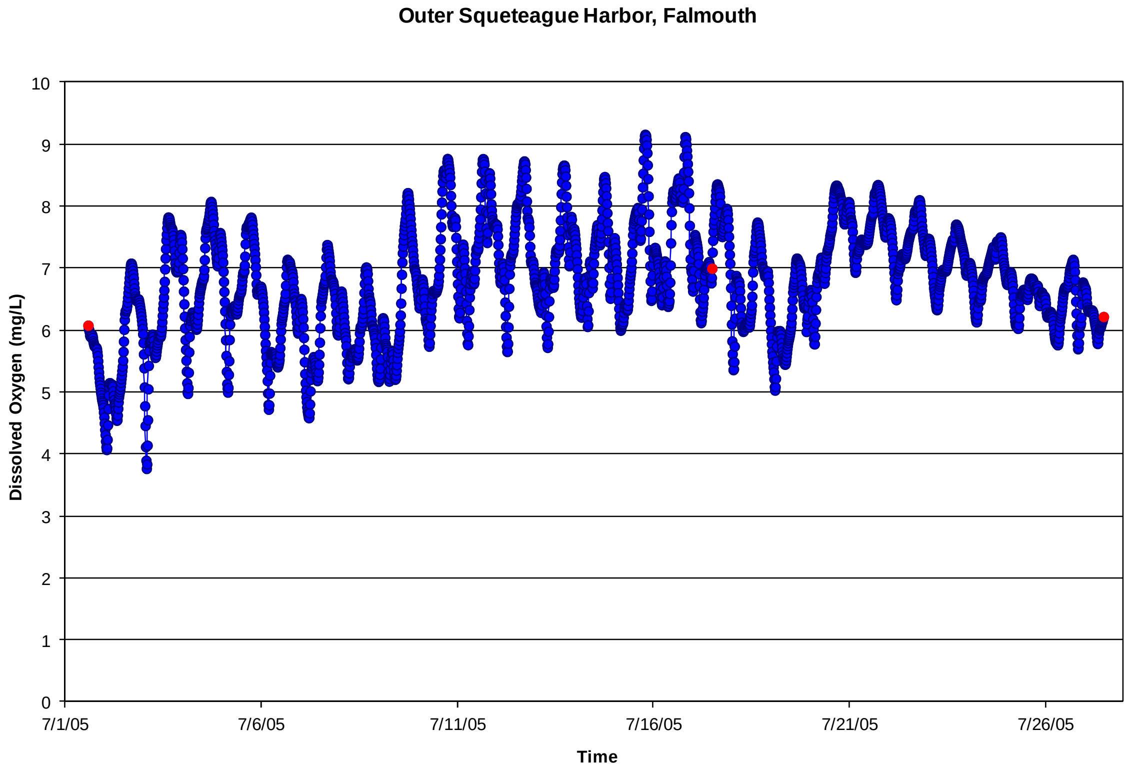


Figure VII-13. Bottom water record of dissolved oxygen at the Squeteague Harbor Outer station, Summer 2005. Calibration samples represented as red dots.

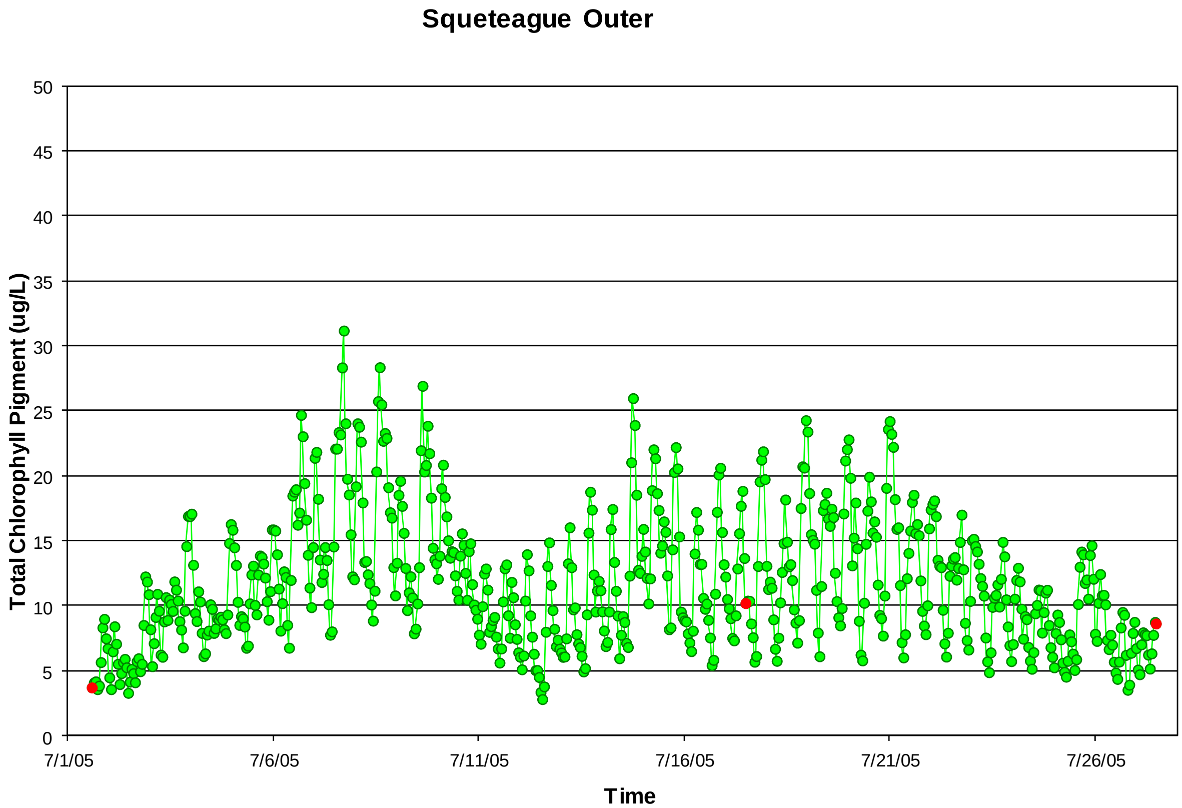


Figure VII-14. Bottom water record of Total pigment at the Squeteague Harbor Outer station, Summer 2005. Calibration samples represented as red dots.

Table VII-1. Days and percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels within the Megansett Harbor and Squeteague 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)
Megansett Outer 1	**7/29/2005**	**9/9/2005**	**42.0**	**31%**	**5%**	**1%**	**0%**
			Mean	0.29	0.12	0.13	0.14
			Min	0.02	0.02	0.02	0.14
			Max	1.61	0.43	0.29	0.14
			S.D.	0.27	0.10	0.15	NA
Megansett Outer 2	**6/23/2006**	**8/1/2006**	**38.9**	**91%**	**69%**	**28%**	**8%**
			Mean	1.36	0.49	0.15	0.10
			Min	0.03	0.01	0.01	0.01
			Max	7.89	2.41	0.63	0.41
			S.D.	1.86	0.47	0.13	0.09
Megansett Outer 3	**7/29/2005**	**9/9/2005**	**41.9**	**36%**	**4%**	**0%**	**0%**
			Mean	0.35	0.13	0.06	NA
			Min	0.01	0.03	0.03	0.00
			Max	2.73	0.32	0.09	0.00
			S.D.	0.43	0.09	0.04	NA
Squeteague Outer	**7/1/2005**	**7/27/2005**	**25.9**	**18%**	**2%**	**0%**	**0%**
			Mean	0.19	0.09	0.03	NA
			Min	0.01	0.01	0.03	0.00
			Max	0.89	0.21	0.03	0.00
			S.D.	0.22	0.07	NA	NA
Squeteague Mid	**7/1/2005**	**7/27/2005**	**26.0**	**5%**	**1%**	**0%**	**0%**
			Mean	0.09	0.05	NA	NA
			Min	0.01	0.03	0.00	0.00
			Max	0.24	0.07	0.00	0.00
			S.D.	0.07	0.02	NA	NA
Squeteague Inner	**6/21/2006**	**8/1/2006**	**41.2**	**45%**	**8%**	**0%**	**0%**
			Mean	0.38	0.14	NA	NA
			Min	0.02	0.01	0.00	0.00
			Max	2.00	0.44	0.00	0.00
			S.D.	0.42	0.11	NA	NA

Table VII-2. Duration (days and % of deployment time) that total pigment (chlorophyll-a + pheophytin) levels exceed various benchmark levels within the Megansett Harbor and the Squeteague 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 Site	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)
Megansett Outer 1	**7/29/2005**	**9/9/2005**	**42.0**	**48%**	**14%**	**8%**	**5%**	**3%**
Mean Chl Value = 7.0 ug/L			**Mean**	0.38	0.41	0.38	1.04	0.32
			Min	0.04	0.04	0.04	0.25	0.08
			Max	9.67	3.04	2.33	1.83	0.88
			S.D.	1.32	0.77	0.75	1.12	0.37
Megansett Outer 2	**6/23/2006**	**8/1/2006**	**41.9**	**40%**	**7%**	**1%**	**0%**	**0%**
Mean Chl Value = 5.3 ug/L			Mean	0.32	0.15	0.08	NA	NA
			Min	0.04	0.04	0.04	0.00	0.00
			Max	2.79	0.58	0.13	0.00	0.00
			S.D.	0.47	0.14	0.04	NA	NA
Megansett Outer 3	**7/29/2005**	**9/9/2005**	**41.9**	**35%**	**8%**	**1%**	**0%**	**0%**
Mean Chl Value = 4.7 ug/L			**Mean**	0.61	0.19	0.10	NA	NA
			Min	0.04	0.04	0.08	0.00	0.00
			Max	3.88	0.67	0.13	0.00	0.00
			S.D.	0.90	0.18	0.02	NA	NA
Squeteague Outer	**7/1/2005**	**7/27/2005**	**25.9**	**96%**	**57%**	**24%**	**8%**	**1%**
Mean Chl Value = 11.8 ug/L			**Mean**	1.91	0.29	0.18	0.14	0.07
			Min	0.04	0.04	0.04	0.04	0.04
			Max	9.88	1.42	0.42	0.29	0.13
			S.D.	3.53	0.26	0.11	0.08	0.04
Squeteague Mid	**7/1/2005**	**7/27/2005**	**26.0**	**96%**	**43%**	**20%**	**10%**	**5%**
Mean Chl Value = 11.2 ug/L			**Mean**	1.91	0.30	0.31	0.23	0.14
			Min	0.33	0.04	0.04	0.04	0.04
			Max	10.00	2.75	1.17	0.46	0.42
			S.D.	2.67	0.48	0.32	0.14	0.12
Squeteague Inner	**6/21/2006**	**8/1/2006**	**41.2**	**98%**	**58%**	**23%**	**5%**	**1%**
Mean Chl Value = 11.6 ug/L			**Mean**	4.49	0.61	0.23	0.17	0.11
			Min	0.33	0.04	0.04	0.04	0.08
			Max	26.88	3.71	0.96	0.42	0.17
			S.D.	8.46	0.88	0.21	0.12	0.05

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass distribution and analysis of historical data was conducted for the Megansett Harbor and Squeteague Harbor Embayment System by the MassDEP Eelgrass Mapping Program as part of the MEP technical effort. Field surveys of the two harbors were conducted in 1995, 2001 and 2012 by MassDEP, as part of this program, with additional observations during summer and fall 2005 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 across the watershed, however this coverage could not be verified and was not used for threshold analysis for Squeteague Harbor. The primary use of the eelgrass data within the MEP approach is to indicate: (a) if eelgrass once or currently colonizes a basin and (b) any large-scale system-wide shifts in distribution. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 to 2012 (Figure VII-15). These data were also compared with an eelgrass survey in the mid 1980's (Costa 1988a,b), thus increasing the validity of the overall assessment of eelgrass trends in Megansett Harbor (inclusive of Fiddlers Cove and Rands Harbor). This temporal information can be used to determine the stability of the eelgrass community in many systems.

All of the available information on eelgrass within the Megansett/Squeteague Estuarine System indicates that the outer basin has and continues to support significant eelgrass beds, though there is some evidence of a decline in acreage over the past 6 decades which is clearly seen in surveys since 1995 where field verification was performed. The absence of significant eelgrass habitat within the channel and Squeteague Harbor indicates that benthic infauna habitat is the focal resource for assessment of impairment by nitrogen enrichment in these basins, while eelgrass habitat should be the focus within the outer basin of Megansett Harbor.

Temporal changes in eelgrass distribution within Megansett outer basin from the 1995-2012 surveys suggests shrinkage of beds located in the northern cove and a "retreat" from the deeper water in the beds bordering the southern margin. The observed pattern of loss of beds from deeper to shallower water is typical of loss resulting from nitrogen enrichment through increased turbidity and decreased light penetration. Although the total pigment levels are only moderate, 7.0 ug L^{-1} and 5.3 ug L^{-1} in the northern cove and southern margin, respectively, the water is sufficiently deep for this to limit light penetration to the bottom, restricting eelgrass habitat to the shallow areas. While the Megansett/Squeteague Estuary does support some of the highest water quality of estuaries on Buzzards Bay, the recent apparent gradual decline in eelgrass habitat indicates that this system is at or just beyond its threshold level of nitrogen enrichment and further increases in nitrogen loading will almost certainly drive a significant decline in eelgrass habitat in the system.

Other factors which influence eelgrass bed loss in embayments may also be at play in the Megansett/Squeteague Estuary. While the general loss seems completely in-line with nitrogen enrichment, localized losses within the Harbor from these other factors are possible. Therefore, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, as the outer basin does not support a high density of boat moorings in the areas where eelgrass habitat is prevalent as well as in areas where loss has occurred. Similarly, pier construction (virtually non-existent) and boating pressure may be adding additional stress but seem to be relatively minor factors in the overall system. However, stress associated with boating activities cannot be ruled out relative to the possible loss from the northern cove area.

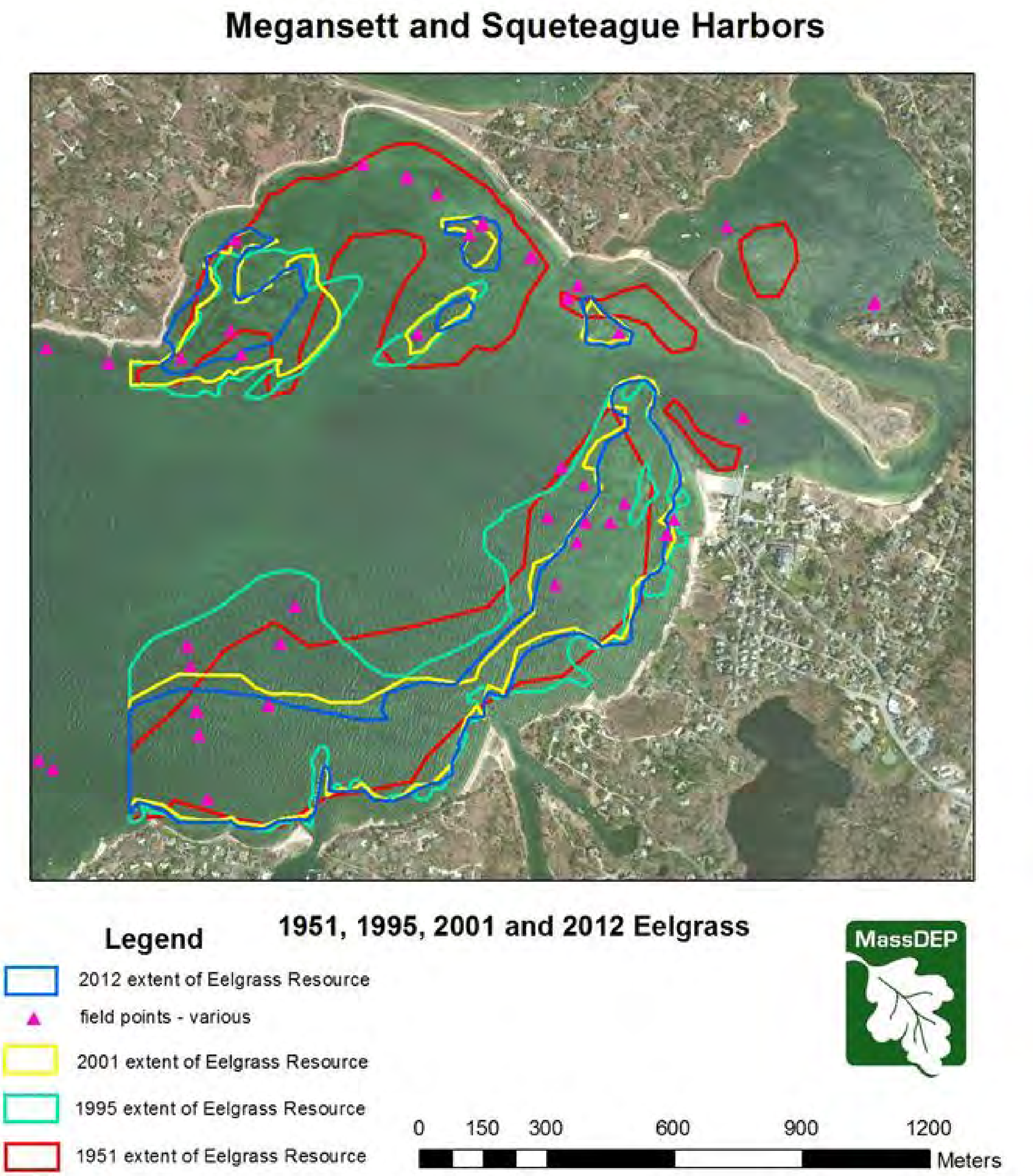


Figure VII-15. Eelgrass bed distribution in the Megansett Harbor and Squeteague Harbor embayment system. 1951 beds delineated using aerial photography are circumscribed by the brown outline and beds delineated in 2012 using underwater video surveying are outlined in blue. Field verification points represented by pink triangles (map from the MassDEP Eelgrass Mapping Program). No eelgrass was observed in Fiddlers Cove or Rands Harbor in 1995, 2001 or by SMAST-MEP surveys conducted in 2006.

Based on the available data from the 1995-2012 surveys, it is possible to estimate the extent to which eelgrass beds might be recovered if nitrogen management alternatives were implemented (Figure VII-15). This determination is based upon the MassDEP Mapping Program and would indicate that the existing eelgrass coverage could be conservatively enhanced by ~20% within the outer harbor basin with nitrogen remediation (Table VII-3).

Table VII-3. Change in eelgrass coverage within the Megansett / Squeteague Harbor Estuarine System, Towns of Bourne and Falmouth, as determined by the MassDEP Eelgrass Mapping Program (C. Costello).

EMBAYMENT	1951 (acres)	1995 (acres)	2001 (acres)	2012 (acres)	% Difference (1995 to 2012) (2001 to 2012)
Megansett / Squeteague Hrb.	185.09	160.25	110.95	101.28	37% 9%
There is presently no eelgrass in the Squeteague Harbor portion of the overall embayment system.					

The relative pattern of habitat quality based upon the eelgrass data is consistent with the results of the oxygen and total pigment time-series data (Section VII.2), nitrogen levels within the inner and outer basins (Section VI) and the benthic infauna analysis (Section VII.4). The absence of eelgrass beds from the inner basins and significant coverage in the outer basin is supported by the low phytoplankton levels (low turbidity) and low nitrogen levels in the outer versus inner basin waters and both the pattern of coverage and the associated levels of the key nutrient related water quality parameters are typical of nutrient enriched shallow embayments (see below). Overall, it appears that the Megansett/Squeteague Estuary has slightly exceeded its assimilative capacity for nitrogen with the resulting recent gradual decline in eelgrass coverage.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted in 2005 at 12 and 7 locations respectively within the Megansett Harbor and Squeteague Harbor portions of the overall embayment system (Figure VII-16), with replicate assays at each site. Because of the elapsed time, it was decided to resample two thirds of the stations in 2014 to confirm the results of the 2005 infaunal survey. In 2014 sampling was conducted at 7 and 6 locations respectively within the Megansett Harbor and Squeteague Harbor. The stations in both years were the same except that 1 station (MG-21) was added in 2014. It is important to note that while fewer stations were sampled in 2014, the stations that were sampled were also stations sampled in 2005. Statistical analysis of the results from the 2 surveys for number of species and individuals showed no significant difference ($p<0.20$ for Megansett; $p<0.21$ for Squeteague). This is consistent with the generally stable nutrient related water quality in this system over the past decade. As a result the results from the 2 surveys were pooled for the analysis of benthic infaunal communities in this estuarine system.

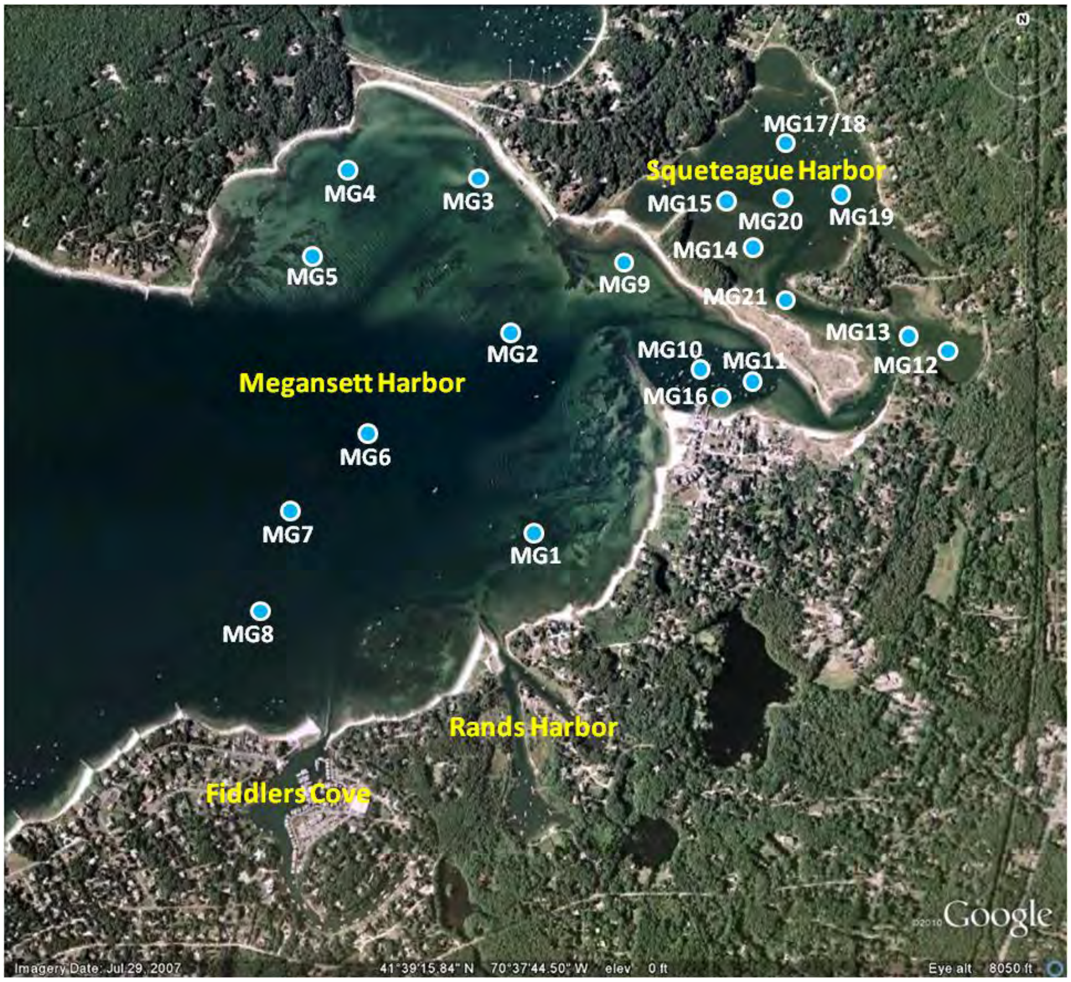


Figure VII-16. Aerial photograph of the Megansett Harbor and Squeteague Harbor system showing location of benthic infaunal sampling stations (blue symbols) sampled in 2005 and 2014.

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 does not appear that the Squeteague Harbor system has ever supported significant eelgrass beds (and no verifiable habitat) and does show signs of some organic enrichment (total pigment levels of >10 ug L^{-1}), and nitrogen enrichment, it may still support moderate to high benthic animal habitat (see below), but it may also be reaching its ability to assimilate additional nitrogen without impairment. To the extent that these two linked estuarine basins can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of 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 total pigment 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.

Megansett / Squeteague Harbor Benthic Animal Community Characteristics:

Overall, the infauna surveys indicated that the Megansett/Squeteague Estuarine System is currently supporting highly productive and diverse benthic communities throughout its component tidal basins. However, there is a modest gradient in benthic community metrics with highest quality habitat in the Megansett Harbor basin closest to the high quality waters of Buzzards Bay to the moderate to high quality habitat in the northern region of Squeteague Harbor, furthest from Buzzards Bay and with the lowest flushing rate (Table VII-4).

Both the northern cove and the southern region bordering the deep basin are supporting eelgrass beds which are relatively stable, but showing a gradual decline from 1995-2012. Not surprising these areas are also supporting high quality benthic animal habitat with high numbers of species (22) and moderate numbers of individuals with high diversity (~3.25) and evenness (~0.75). Equally important is the very low numbers of stress and organic indicator species (tubificids and capitellids) and numbers of mollusks and crustaceans. These results are consistent with the generally moderate levels of oxygen depletion and low total pigment (chlorophyll-a + pheophytin), ~5 ug L^{-1} (indicative of low organic matter loading). The channel between Megansett Harbor and the main basin of Squeteague Harbor also shows high quality benthic animal habitat with metrics approaching the outer basin. The channel supports a diverse community (H'=3.28) with high Evenness (E=0.79) with moderate to high numbers of species (19) and individuals (~200). However, stress indicator species, mainly tubificids, were present and represented as much as 20% of the community. While the community was found to be representative of high quality habitat, the presence of these stress indicators should be tracked. However, it is possible that disturbance due to the high velocity flows in the channel and boating activities may play a role along with the deposition stemming from the drop in velocity as the channel widens at either end. This latter disturbance possibility is supported by the observation that these stress indicators were sparse in the innermost basin, Squeteague Harbor. Squeteague Harbor also showed moderate to high quality benthic animal habitat with moderate to high numbers of species (15-19), diversity (H'=2.90-3.36) and high numbers of individual (160-260) and Evenness (E=0.75-0.80). There is some indication of organic enrichment as amphipods dominate some areas (*Ampelisca*), which suggests that this basin may be nearing its ability to assimilate additional nitrogen without impairment. This is consistent with the moderate total pigment (chlorophyll-a + pheophytin) levels, averaging 11-12 ug L-1 in the time-series and 9.8 - 10.8 in the long-term grab sample record (BayWatchers 2000-2014).

Table VII-4. Benthic infaunal community data for the Megansett Harbor and Squeteague Harbor embayment system (2005, 2014 surveys). 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 m^2). Stations refer to map in Figure VII-13.

Location	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)	Stations (MGS-)
Megansett Harbor						
North Cove	22	125	19	3.25	0.74	3,4,5
South Margin	22	219	17	3.23	0.75	1,2,6,7,8
Channel						
Megan-Squet	19	196	15	3.28	0.79	10,11,12,13
Squeteague Harbor						
North Basin	15	261	12	2.90	0.75	15,16,17,19,20
South Basin	19	159	15	3.36	0.80	14, 21
* Station numbers refer to locations in Figures VII-16 and VII-17						

The spatial pattern of benthic habitat quality is similar to other estuaries on Buzzards Bay with similar water quality and specific nitrogen loading. For example the main basin of the Fiddlers Cove Embayment System (part of this system previously assessed) is presently supporting moderate to high quality benthic habitat with 21 species and ~300 individuals per sample with high diversity (Weiner Diversity Index, H' and Evenness, having values of 3.4 and 0.77, respectively. The community includes diverse communities of polychaetes, mollusks and crustaceans. This pattern of higher organic enrichment and lower habitat quality in the inner versus outer regions is common to estuaries in general. But in the case of Megansett/Squeteague Harbors the gradient, while apparent, is not dramatic, with the inner basin suggesting that the assimilative capacity for nitrogen is presently being reached.

The benthic animal communities were compared to the highest quality environments in the region, such as the Outer Basin of Quissett Harbor. 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 (up to 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. The Megansett/Squeteague basins, particularly the open water basin of Megansett Harbor has metrics approaching these systems.

Across Buzzards Bay in the similarly configured unimpaired basins of Nasketucket Bay, Shaws Cove and Little Bay were also assessed by the MEP. Assessment of the benthic community in the upper region of Shaws Cove has a relatively high number of species (20) and number of individuals (~250 per 0.0625 m^{-2} grab), with moderate diversity (H'= 2.5) and Evenness (E=0.6). Generally high quality benthic habitat supports an average species number $\geq$ 20 per sample. The community was dominated by a mix of polychaetes and crustaceans with some mollusks and few organic enrichment indicator species. The lack of high organic enrichment was seen in the generally low organic matter sediments dominated by fine sands with mud with an oxidized surface. This is similar to regions of the Megansett/Squeteague Estuary. Similarly, Little Bay, the largest tributary basins to Nasketucket Bay, has not historically supported eelgrass coverage. Little Bay is currently supporting moderate to high quality infauna habitat, with a relatively high number of species (20) and number of individuals (~300 per 0.0625 m^{-2} grab), with high diversity (H' >3.0) and Evenness (E=0.69). The community was dominated by a mix of polychaetes and crustaceans with some mollusks with deep burrowers present.

Finally, nearby Phinneys Harbor similarly configured to Megansett Harbor main basin has a similar range of depths and sediment types. The central basin is >4 meters in depth with marginal areas <1.5 meters. The deep basin areas typically support fine grained sands and muds, while the margins also have gravels and rocks. Phinneys Harbor basin overall is presently supporting a healthy infaunal habitat with infaunal communities of 20-25 species and ~250 or more individuals. Diversity and Evenness were lower than Megansett Harbor but high, generally >2.5 and >0.65, respectively. Equally important, the community was dominated by mollusks and crustaceans (40 species total) with polychaetes comprising 44% or 31 of the total species observed. The polychaetes were dominated by hesonids. There were deep burrowing forms (e.g. *Tellina, Tagelus*), shellfish (Mercenaria, Mya) and numerous large burrows noted in the field surveys. These results are comparable to those from Megansett Harbor, as noted above.

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 benthic infauna habitat of Megansett Harbor and the channel to Squeteague are consistent with low organic enrichment and in line with similar basins within Buzzards Bay. It also appears that Squeteague Harbor is showing moderate to high quality habitat consistent with modest organic matter loading and nitrogen enrichments. While this basin presently supports quality habitat it appears to be approaching its threshold for assimilating nitrogen without becoming impaired.

Nitrogen levels throughout this estuarine system are consistent with the general lack of impaired benthic animal habitat. Total nitrogen levels are highest within the enclosed basin of Squeteague Harbor, (0.448 mg L^{-1} tidally averaged) where levels over 0.500 mg L^{-1} are generally found in areas showing signs 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 as available to the MEP Technical Team. 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-17). As is the case with some systems on Cape Cod, all of the enclosed waters of Squeteague Harbor are classified as conditionally approved for the taking of shellfish during specific portions of the year, indicating the system is moderately impaired relative to the taking of shellfish. This could be due to bacterial concerns which would be a result of both human activity (septic systems in the watershed) as well as natural fauna, however, it may also be related to the historic oil spill that occurred in Buzzards Bay and significantly affected Wild Harbor. Unlike Squeteague Harbor, Megansett Harbor is approved for shellfishing year round. Despite the conditionally approved status of Squeteague Harbor, both components (Megansett and Squeteague) of the overall embayment system have also been classified as supportive of specific shellfish communities (Figure VII-18). The major shellfish species with potential habitat within the Megansett Harbor portion of the system are Bay Scallop and quahogs (*Mercenaria*). Habitat theoretically suitable to *Mercenaria* and the American oyster can be found throughout the main basin of Squeteague Harbor extending slightly into the narrow channel that constitutes the inner portion of Megansett Harbor inside the rocky breakwater. Theoretically small areas of suitable habitat for *Mya* is essentially situated along the shallow waters at the upper edge of the main basin of Megansett Harbor relatively close to the Sunrise Beach and Eustis Beach area of Scraggy Neck.

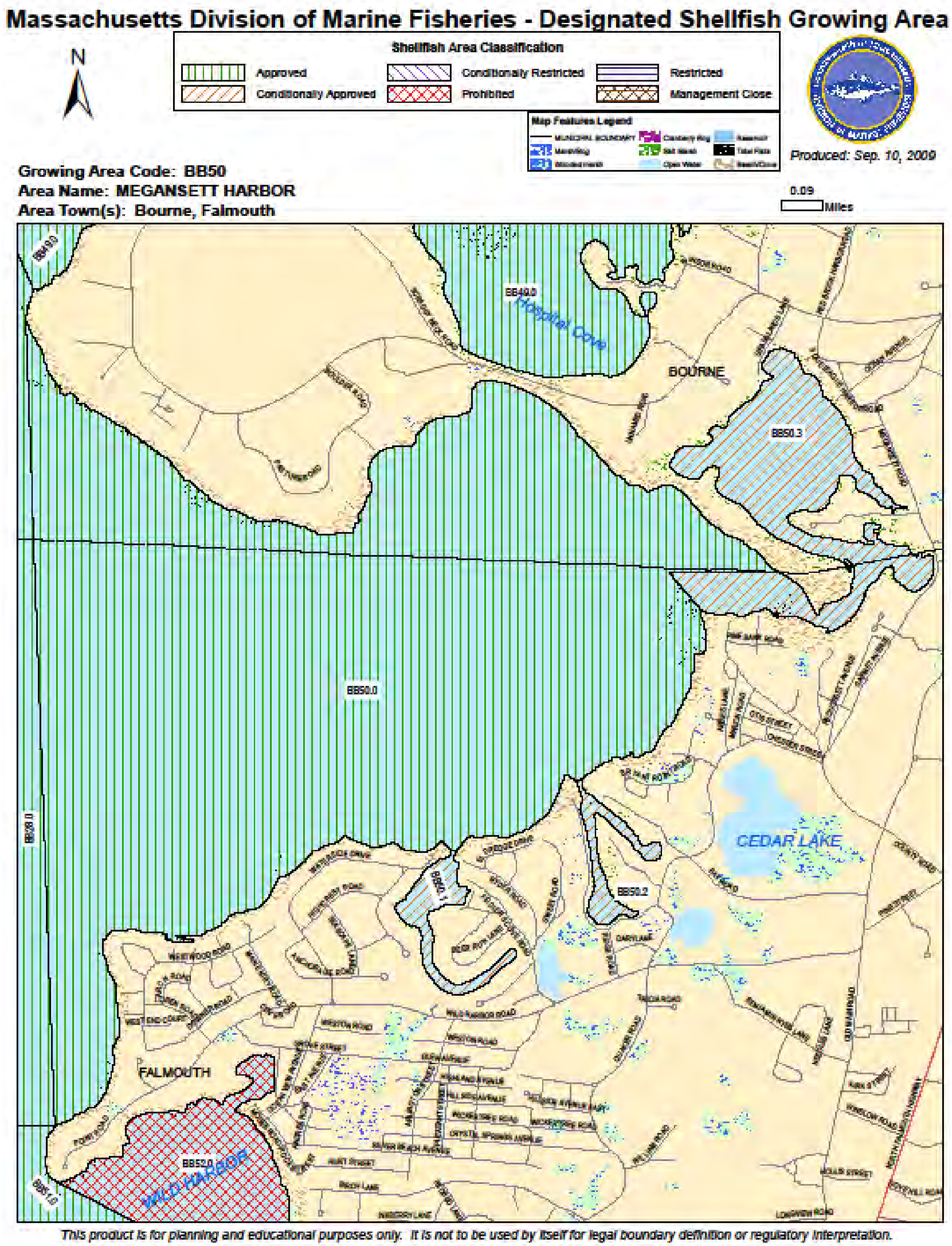


Figure VII-17. Location of shellfish growing areas in the Megansett Harbor and the Squeteague Harbor embayment system and the status relative to shellfish harvesting as determined by Massachusetts Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

Megansett Harbor and Squeteague Harbor Shellfish Suitability Areas (Mass GIS Online Mapping)

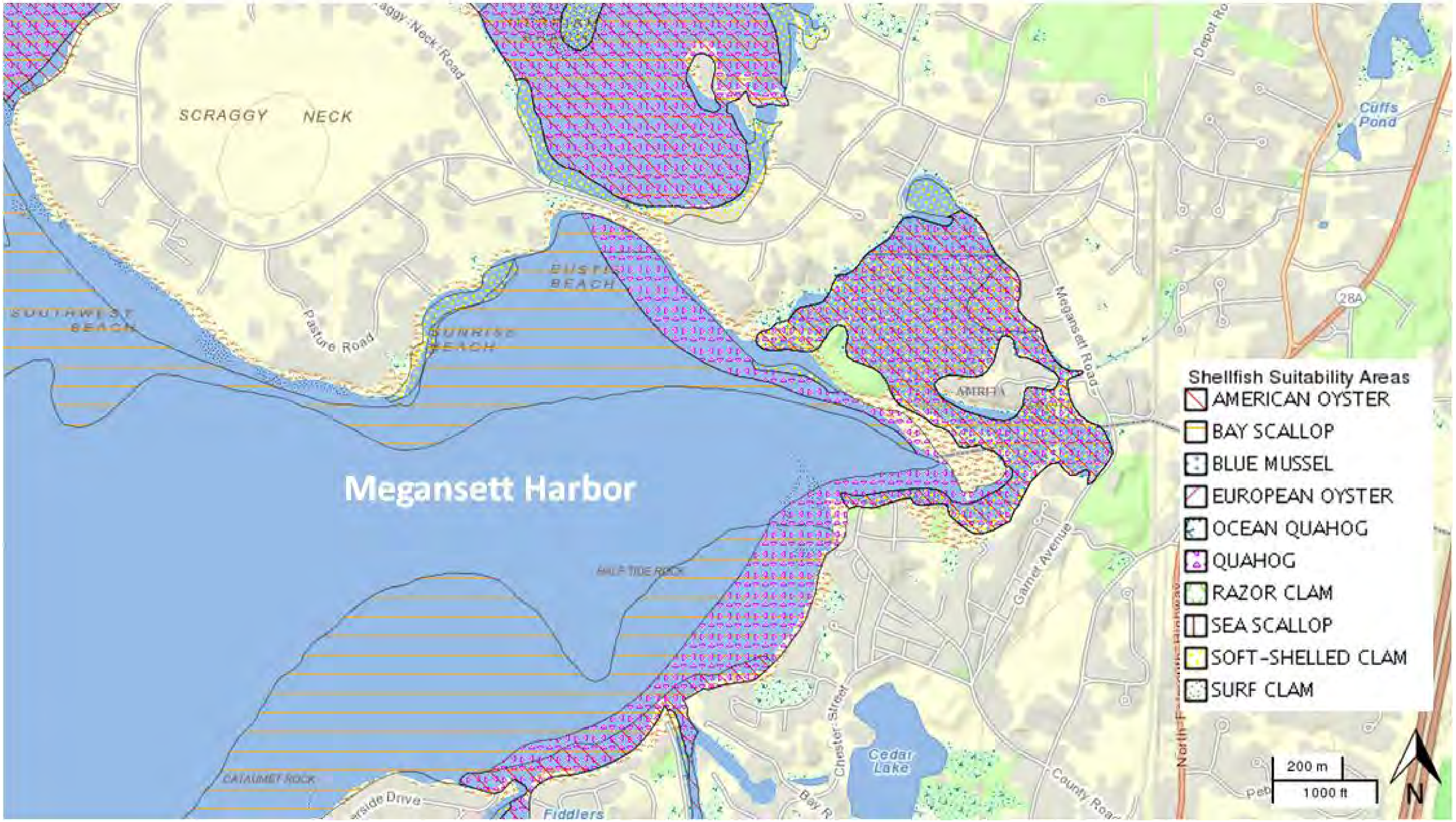


Figure VII-18. Location of shellfish suitability areas within the Megansett Harbor and Squeteague Harbor embayment system as determined by Massachusetts Division of Marine Fisheries. Suitability does not necessarily mean "presence".

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 Megansett/Squeteague Harbor Estuarine System by the MEP and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline Water Quality Monitoring Program conducted by the Coalition for Buzzards Bay's BayWatchers with analytical support from the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth (through 2008).

The Megansett/Squeteague Harbor Estuarine System is a complex estuary created by rising sea-level entering the large basin of Megansett Harbor and later an associated cove where coastal processes created a barrier beach to form the tributary sub-embayment, Squeteague Harbor. Smaller component estuaries, Fiddlers Cove and Rands Harbor were formed as drowned "river" valley estuaries and exchange tidal water with the outer southern region Megansett Harbor (assessed previously, Howes et al., 2011). Megansett Harbor consists of a large basin which directly exchanges tidal waters with Buzzards Bay, with a deep central region (>5 meters) and large marginal shallows which currently support eelgrass. Squeteague Harbor is enclosed and exchanges tidal waters through a long channel to Megansett Harbor. While there is some fringing salt marsh, both Harbors are currently functioning as typical coastal embayment basins with free tidal exchange with the waters of Buzzards Bay. Each type of functional component to an estuary (salt marsh basin, embayment, tidal river, deep basin {sometimes drowned kettles}, shallow basin, etc.) has a different natural sensitivity to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of the specific basin and its ability to support eelgrass beds and infaunal communities. At present, the Megansett/Squeteague 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 eelgrass (Megansett basin) and appears to be approaching its nitrogen loading limit relative to sustaining high quality infaunal habitats within the inner reaches of Squeteague Harbor (Table VIII-1). The biologic criteria for measuring impairment are indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

The measured levels of oxygen depletion and total pigment (chlorophyll-a + pheophytin) levels follows the spatial pattern of total nitrogen levels in this system (Section VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment. The spatial pattern indicated that the magnitude of organic matter enrichment of sediments, enhancement of total pigment levels and total nitrogen concentrations increased from the offshore waters to the Megansett Harbor basin and were highest within the inner reaches of Squeteague Harbor.

Oxygen records obtained from the moorings (6) deployed throughout the Megansett/Squeteague Harbor Estuarine System indicate moderate organic matter enrichment resulting in periodic low to moderate oxygen depletion within both Megansett Harbor and

Squeteague Harbor basins. Oxygen stress was only indicated within the deepest portion of Megansett Harbor which is a natural depositional area receiving both phytoplankton deposition and macrophyte detritus (macroalgal and eelgrass). This basin may also be influenced by discharging high nutrient waters from Fiddlers Cove and Rands Harbor whose tidal inlets are only close to the margin of the deep basin.

Oxygen in the nearshore adjacent eelgrass beds in the north cove region (basin adjacent Eustis Beach) had only moderate daily excursions, ranging from levels at or just above air equilibration declining briefly to 5 mg L^{-1} and oxygen in bottom water was found to be >5 mg L^{-1}, 95% of the record and was >6 mg L^{-1} in 97% of the BayWatcher grab samples (N=37). The low organic enrichment of the system is also demonstrated by the general lack of algal blooms with the exception of 1 bloom observed during the later part of the meter deployment period (first week of September). That bloom corresponded to higher rates of photosynthesis (carbon fixation) and larger oxygen excursions and rapid declines in oxygen after sunset stemming from respiration. However, on average chlorophyll a levels were 7.0 ug L^{-1} and 5.4 ug L^{-1} in the long-term record (BayWatcher grab samples, N=52).

Similarly, oxygen in at the margin of the outer basin in more open water than the two other Megansett Harbor also showed only relatively low daily excursions (~2 mg L^{-1}) in oxygen levels, with few excursions above air equilibration and bottom water oxygen above 4 mg L^{-1}. Oxygen levels regularly persisted between 5 and 7 mg L^{-1} and occasionally exceeded 8 mg L^{-1}. These moderate oxygen levels are primarily the result of respiration by low to moderate phytoplankton biomass and relatively quiescent waters. The oxygen levels and excursions were typical of relatively low organic enrichment, consistent with the general lack of algal blooms. only a single small bloom to ~10 ug L^{-1}, with average total pigment levels of 4.7 ug L^{-1} (MG-4 BayWatcher 5.1 ug L^{-1}, N=52). The low frequency of oxygen depletion observed in this system is indicative of high quality habitat, which is also consistent with the generally low total pigment levels, also indicative of low nitrogen enrichment in this portion of Megansett Harbor. In this portion of the main basin of Megansett Harbor, total pigment exceeded the 10 ug L^{-1} benchmark only 8 percent of the time and conditions were consistent with the open water nature of the basin and its free exchange with high quality Buzzards Bay waters.

In contrast, in the deepest waters of the main basins, low to moderate daily excursions in oxygen levels were observed, but overall oxygen levels periodically declined to 2-4 mg L^{-1}. Instantaneous oxygen levels that frequently drop to 2-4 mg L^{-1} are indicative of oxygen stress. It appears likely that some of the oxygen depletion at this site is due to the structure of the basin, where organic matter deposition occurs in the deep water off shore of the eelgrass beds in the shallows and outflows from Fiddlers Cove and Rands Harbor. The low oxygen does not appear to be related to nitrogen or total pigment levels (average 5.3 ug L^{-1} in time-series record, 6.3 ug L^{-1} long-term record from BayWatchers) or particulate carbon concentrations (0.102 mg L^{-1}) which are low for estuarine waters in s.e. Massachusetts. It is likely that the low oxygen in the "hole" is the result of the region being a "particle trap" similar to the 3 deep basins in Nantucket Harbor. These Nantucket Harbor basins were observed to collect organic matter and macrophyte detritus (macroalgae and eelgrass) from the adjacent shallows. Accumulation of macrophyte detritus in this area of Megansett basin was confirmed by diver observations (S. Aubrey personal communication). The lower oxygen levels compared to the other two mooring locations in Megansett Harbor are inconsistent with the generally low total pigment levels in this portion of Megansett Harbor (average total pigment by mooring, 5.3 ug L^{-1}). In this portion of the main basin of Megansett Harbor, total pigment exceeded the 10 ug L^{-1} benchmark only 7 percent of the time. It appears that like Nantucket Harbor, the deep basin of Megansett Harbor has periodic oxygen depletion related to its structure as a natural depositional area, rather than local processes related to eutrophication.

The enclosed shallow basin of Squeteague Harbor has similar oxygen conditions as the shallower marginal areas of Megansett Harbor and tended to show less oxygen depletion than the deep basin of Megansett Harbor. Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of potential oxygen stress, but that has not been observed within Squeteague Harbor. Within the eastern section of the main basin furthest removed from the inlet connecting the Megansett Harbor basin to the Squeteague Harbor basin, only relatively small daily excursions in oxygen levels were observed, ranging from levels at or just above air equilibration to slightly less than 5 mg L^{-1}. At this inner Squeteague mooring site, oxygen levels regularly persisted between 5 and 7 mg L^{-1} and periodically reached 8 mg L^{-1}. These moderately high oxygen levels are primarily the result of photosynthesis and ventilation from vertical mixing of the shallow watercolumn. Oxygen levels that drop below 4 mg L^{-1} are indicative of potential oxygen stress and that did not occur at this site or the other sites in Squeteague Harbor. Moderate organic enrichment was observed through both the fine grained organic sediments and the elevated total pigment levels associated with a prolonged phytoplankton bloom that took place during the first three weeks (June into July) of the record (total pigment in the 10-15 ug L^{-1} range during the bloom) and through the average total pigment over the summer of 11.6 ug L^{-1}. Similarly, long-term water quality monitoring indicates chlorophyll-a levels of 9.8 and 10.8 ug L^{-1} were typical of summer conditions (averages of SQ1 and SQ2, respectively, BayWatchers).

The western section of the main basin also had only moderate daily excursions in oxygen levels (~4 mg L^{-1}), ranging from levels at or just above air equilibration to 5 mg L^{-1} and very occasionally to 4 mg L^{-1}. Oxygen levels regularly persisted between 6 and 10 mg L^{-1} with few low oxygen periods (4-5 mg L^{-1}). Over the 26 day deployment there appears to be one moderately intense phytoplankton bloom where total pigment (chlorophyll-a + pheophytin) increased to 15-20 ug L^{-1} with a short period of bloom activity where total pigment concentrations were 25-30 ug L^{-1}. The generally high oxygen levels of >6 mg L^{-1} during 95% of the record do not indicate stress or benthic animal habitat impairment. This is also consistent with the total nitrogen levels in the system (0.45 mg L^{-1}, tidally averaged) and observed total pigment levels that are consistent with moderate nitrogen enrichment of Squeteague Harbor (average total pigment, 11.2 ug L^{-1}). In this portion of the main basin of Squeteague Harbor, total pigment exceeded the 10 ug L^{-1} benchmark 43 percent of the record. Average total pigment levels over 10 ug L^{-1} have been used to indicate eutrophic conditions in embayments.

Finally, at the measurement site nearest the tidal inlet, situated approximately 600 meters from the throat of the inlet. only moderate daily excursions (~3 mg L^{-1}) in oxygen levels were observed, with oxygen ranging from just above air equilibration to 4-5 mg L^{-1}. Oxygen remained above 5 mg L^{-1} 98% of the record. Oxygen levels regularly persisted between 5 and 8 mg L^{-1}. These moderately high oxygen levels are primarily the result of photosynthesis by phytoplankton and ventilation of bottom waters by vertical mixing of the shallow watercolumn. Oxygen levels that drop below 4 mg L^{-1} are indicative of potential oxygen stress and this was not observed at any of the Squeteague sites. The moderate organic enrichment of the system is also demonstrated by the elevated total pigment levels associated with two observed algal blooms that took place during the second and fourth weeks (July) of the meter deployment period (averaging 11.8 ug L^{-1} with periods of 15-20 ug L^{-1} and peaks to just over 25 ug L^{-1}. That bloom corresponded to higher rates of photosynthesis (carbon fixation) and larger oxygen excursions and rapid declines in oxygen after sunset stemming from respiration.

Overall conditions within the Squeteague Harbor basins include generally high oxygen levels, with only moderately total pigment level (~11 ug L^{-1}), stemming from the moderate nitrogen enrichment (TN <0.50 mg L^{-1}). These conditions are generally associated with low stress to benthic animal communities.

The observed watercolumn metrics (oxygen, total pigment as chlorophyll-a + pheophytin, total nitrogen) are consistent with the infaunal communities within the Megansett/Squeteague estuarine basin. The infauna surveys indicated that the Megansett/Squeteague Estuarine System is currently supporting highly productive and diverse benthic communities throughout its component tidal basins. However, there is a modest gradient in benthic community metrics with highest quality habitat in the Megansett Harbor basin closest to the high quality waters of Buzzards Bay of Megansett Harbor to the moderate to high quality habitat in the northern region of Squeteague Harbor, furthest from Buzzards Bay and with the lowest flushing rate.

Both the northern cove and the southern region bordering the deep basin of Megansett Harbor are supporting eelgrass beds which are relatively stable, but showing a gradual decline from 1995-2012. Not surprising these areas are also supporting high quality benthic animal habitat with high numbers of species (22) and moderate numbers of individuals with high diversity (~3.25) and evenness (~0.75). Equally important is the very low numbers of stress and organic indicator species (tubificids and capitellids) and numbers of molluscs and crustaceans. Similarly, the channel between Megansett Harbor and the main basin of Squeteague Harbor also shows high quality benthic animal habitat with metrics approaching the outer basin. The channel supports a diverse community (H'=0.328) with high Evenness (E=0.79) with moderate to high numbers of species (19) and individuals (~200). However, stress indicator species, mainly tubificids, were present and represented as much as 20% of the community. While the community was found to be representative of high quality habitat, the presence of these stress indicators should be tracked. However, it is possible that disturbance due to the high velocity flows in the channel and boating activities may play a role along with enhanced deposition stemming from the drop in velocity as the channel widens at either end. This localized disturbance effect is supported by the observation that these stress indicators were sparse in the innermost basin, Squeteague Harbor. Squeteague Harbor also showed moderate to high quality benthic animal habitat with moderate to high numbers of species (15-19), diversity (H'=2.90-3.36) and high numbers of individual (160-260) and Evenness (E=0.75-0.80). There is some indication of moderate organic enrichment as amphipods dominate some areas (*Ampelisca*), which suggests that this basin may be nearing its ability to assimilate additional nitrogen without impairment. This is consistent with the moderate total pigment levels, averaging 11-12 ug L-1 in the time-series and 9.8 - 10.8 in the long-term grab sample record (BayWatchers 2000-2014) and average total nitrogen of 0.45 mg L^{-1}.

The spatial pattern of benthic habitat quality is similar to other estuaries on Buzzards Bay with similar water quality and specific nitrogen loading. For example the main basin of the Fiddlers Cove Embayment System (part of this system previously assessed) is presently supporting moderate to high quality benthic habitat with 21 species and ~300 individuals per sample with high diversity (Weiner Diversity Index, H' and Evenness, having values of 3.4 and 0.77, respectively. The community includes diverse communities of polychaetes, molluscs and crustaceans. This pattern of higher organic enrichment and lower habitat quality in the inner versus outer regions is common to estuaries in general. But in the case of Megansett/Squeteague Harbors the gradient, while apparent, is not dramatic, with the inner basin suggesting that the assimilative capacity for nitrogen may only just now be being reached.

The benthic animal communities were compared to the highest quality environments in the region, such as the Outer Basin of Quissett Harbor. 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 (up to 32), diversity (3.69) and Eveness (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. The Megansett/Squeteague basins, particularly the open water basin of Megansett Harbor has metrics approach these systems. However, benthic animal habitat is generally of high quality throughout the Megansett/Squeteague Harbor Estuary.

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 benthic infauna habitat of Megansett Harbor and the channel to Squeteague are consistent with low organic enrichment, consistent with similar basins within Buzzards Bay. It also appears that Squeteague Harbor is showing moderate to high quality habitat consistent with modest organic matter loading and nitrogen enrichment. While this basin presently supports quality habitat it appears to be approaching its threshold for assimilating nitrogen without becoming impaired.

Nitrogen levels throughout the Megansett/Squeteague Harbor Estuary are consistent with the general lack of impaired benthic animal habitat. Total nitrogen levels are highest within the enclosed basin of Squeteague Harbor, (0.448 mg L-1 tidally averaged) where levels over 0.500 mg L-1 are generally found associated with impairment of benthic animal habitat in southeastern Massachusetts estuaries.

While infauna habitat is generally of high quality throughout the main basins of the Megansett/Squeteague Harbor Estuary, all of the available information on eelgrass within this Estuarine System indicates that although the outer basin of Megansett Harbor continues to support significant eelgrass beds, there is some evidence of a decline in acreage. The decline is in both the southern and northern major eelgrass beds (Section VII.2) and is clearly seen in surveys since 1995 where field verification was performed. The absence of significant eelgrass habitat within the channel and Squeteague Harbor basin indicates that benthic infauna habitat is the main resource for assessment of impairment by nitrogen enrichment and the focus of management for these basins, while eelgrass habitat should be the focus within the outer basin of Megansett Harbor.

Temporal changes in eelgrass distribution within Megansett outer basin from 1995-2012 surveys suggests shrinkage of beds located in the northern cove and a "retreat" from the deeper water in the beds bordering the southern margin. The observed pattern of loss of beds from deeper to shallower water is typical of loss resulting from nitrogen enrichment through increased turbidity and decreased light penetration. Although the total pigment levels are only moderate, 7.0 ug L^{-1} and 5.3 ug L^{-1} in the northern cove and southern margin, respectively, the water is sufficient deep for this to limit light penetration to the bottom, restricting eelgrass habitat to the shallow areas. While the Megansett/Squeteague Estuary does support some of the highest water quality of estuaries on Buzzards Bay, the recent apparent gradual decline in eelgrass habitat indicates that this system is at or just beyond its threshold level of nitrogen enrichment and further increases in nitrogen loading will almost certainly affect a significant decline in eelgrass habitat in the system.

Other factors which influence eelgrass bed loss in embayments may also be at play in the Megansett/Squeteague Estuary. Although the general loss seems completely in-line with nitrogen enrichment, localized losses with the Harbor from these other factors are possible. Therefore, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, as the outer basin does not support a high density of boat moorings in the areas where eelgrass habitat is prevalent as well as in areas where loss has occurred. Similarly, pier construction (virtually non-existent) and boating pressure may be adding additional stress but seem to be relatively minor factors in the overall system. However, stress associated with boating activities cannot be ruled out relative to the possible loss from the northern cove area.

Based on the available data from the 1995-2012 surveys, it is possible to estimate the extent to which eelgrass beds might be recovered if nitrogen management alternatives were implemented (Figure VII-15). This determination is based upon the MassDEP Mapping Program and would indicate that the existing eelgrass coverage could be enhanced by more than 20% within the outer harbor basin with nitrogen remediation.

The relative pattern of habitat quality based upon the eelgrass data is consistent with the results of the oxygen and total pigment time-series data (Section VII.2), nitrogen levels within the inner and outer basins (Section VI) and the benthic infauna analysis (Section VII.4). The absence of eelgrass beds from the inner basins and significant coverage in the outer basin is supported by the low phytoplankton levels (low turbidity) and low nitrogen levels in the outer versus inner basin waters and both the pattern of coverage and the associated levels of the key nutrient related water quality parameters are typical of nutrient enriched shallow embayments (see below). Overall, it appears that the Megansett/Squeteague Estuary has slightly exceeded its assimilative capacity for nitrogen with the resulting recent gradual decline in eelgrass coverage. Determining the nitrogen target to restoring the impaired eelgrass habitat and protecting infauna habitat in the inner basins is the focus of the nitrogen management threshold analysis, below in Section VIII.2.

Table VIII-1. Summary of nutrient related habitat quality within the Megansett/Squeteague Estuarine System within the Towns of Falmouth and Bourne, MA, based upon assessments in Section VII. WQMP indicates BayWatcher Water Quality Monitoring Program.

Health Indicator	Megansett/Squeteague Estuarine System		
	Megansett Harbor	**Channel**	**Squeteague Harbor**
Dissolved Oxygen	H/MI[1]	H/MI[2]	H/MI[2]
Chlorophyll	H[3]	H[4]	H/MI[4]
Macroalgae	H[5]	H/MI[5]	H[6]
Eelgrass	MI[7]	--[8]	--[8]
Infaunal Animals	H[9]	H[10]	H/MI[11]
Overall:	**H/MI[12]**	**H[13]**	**H/MI**

1- deep water oxygen appears to be affected by basin structure, but margins of basin >5 mg/L >95% of record consistent with WQMP which was always >4 mg/L, >5 mg/L at MG-1 97%; MG-2 100%of time.

2 - all 3 moorings oxygen always > 4mg/L , >5 mg/L >92% of time, WQMP: >6 mg/L 77% of samples (N=263), 99% of samples >4 mg/L, only 1% of samples <4 mg/L.

3 - levels low for a coastal basin, averaging ~5 ug L-1 (time series) with <10 ug L-1 >90% of the time and averages 5-6 ug L-1 at all sites in long-term WQMP monitoring.

4 - low to moderate for a coastal basin, Channel average 8.4 ug L^{-1}, Squeteague Basin ~10 ug L^{-1} (WQMP 2000-2014, N=54) with time-series (Squeteague) <20 ug L^{-1} 90% of record, average 11.6 ug.

5- drift algae generally absent, patches of attached Codium (filling the eelgrass niche')

6- sparse to no macroalgae in north basin, patches of Codium in south basin.

7- most of the basin margin supports eelgrass habitat, loss of some fringing beds in the region adjacent the inlet to the channel to Squeteague Harbor basin and along the boundary of the shallow and deep water basin along the southern shore. The temporal and spatial pattern of loss from the inner margin of the beds is typical of nitrogen enrichment and indicates moderate impairment.

8- no documented (verified) evidence of eelgrass "presence" in this basin historically.

9- high numbers of individuals (125-219), species (22), diversity (>3) and Evenness (>0.7), community dominated by non-stress indicator species with crustaceans and mollusks and polychaetes dominant, 10 - community includes polychaetes, crustaceans and molluscs with some organic enrichment tolerant species, tubificids (15%-18% of community); but high diversity (>0.3) and Evenness (0.7), and moderate to high numbers of species (19) and individuals (200).

11 - north basin and south basin continue the trend in infaunal community of lower metrics with increasing distance from offshore waters; both have moderate to high numbers of species (19 vs 15), individuals (160 vs 260) and diversity (H') (3.36 vs 2.9), with high Evenness (>0.7). Organic tolerant species are present in patches (mainly tubificids), but the typical community is dominated by polychaetes with crustaceans and molluscs. Amphipods also present at some locations (*Ampelisca*).

12 -high quality eelgrass habitat from 1995-2012 with only recent loss at the margin to the deep basin area to the south and reductions in patches in the northern cove area, consistent with sandy sediments and low chlorophyll a levels (e.g. high light penetration). Benthic infaunal animal communities are highly diverse and productive relative to others on Cape Cod. Loss of marginal eelgrass coverage is indicative of a nitrogen enrichment and rates a designation of "Moderate Impairment" coupled with a "High Quality" habitat designation based upon the general eelgrass and benthic habitat indicators, low chlorophyll and generally moderate to high D.O.

13 - no eelgrass habitat, but low-moderate levels of phytoplankton biomass, coupled with periodic D.O. depletion to 4 mg/L, with D.O. >5 mg L-1 97% of samples (N=349) from WQMP. Infauna community is indicative of a moderate to high quality habitat with high species (19) and number of individuals (~200), diversity (H'=3.28) and Evenness (E=0.79). Indicative of unimpaired habitat.

14 - no eelgrass habitat with moderate to high quality benthic infauna habitat with moderate to high numbers of species (15-19), diversity (H'=2.90-3.36) and high numbers of individuals (160-260) and Evenness (E=0.75-0.80). There is some indication of organic enrichment as amphipods dominate some areas (*Ampelisca*), suggesting that this basin may be nearing its ability to assimilate additional nitrogen without impairment. This is consistent with the moderate chlorophyll a levels, averaging 11-12 ug L-1 in the time-series and 9.8 - 10.8 in the long-term grab sample record (BayWatchers 2000-2014).

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

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 Megansett / Squeteague Harbor Embayment System is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. Given the information on a variety of key habitat characteristics, it is possible to develop a site-specific threshold, which is a refinement upon more generalized threshold analyses frequently employed.

The Megansett/Squeteague Harbor Estuarine System presently shows a moderate level of impairment to eelgrass habitat within its Outer Basin (Megansett Harbor). The impairment is based upon the recent temporal trend in loss of eelgrass from eelgrass areas in both the northern and southern margins of the basin, particularly where the southern beds impinge upon deeper water. Both the location and the temporal trend is consistent with nitrogen enrichment. However, that the rate of loss has been gradual and relatively recent indicates that this estuary is only just beyond its nitrogen threshold (i.e. the level of nitrogen a system can tolerate without impairment). The presence of stable dense eelgrass beds throughout the shallow margins of Megansett Harbor and the generally high quality benthic animal habitat throughout the embayment system (with only a slight indication of incipient moderate impairment in the innermost reaches of Squeteague Harbor) also indicates a system only just beyond its threshold. The indication of impairment to eelgrass and infaunal animal habitat, to the extent that it was observed, is supported by the observed levels of oxygen depletion and clearly enhanced total pigment levels in the Inner Basin waters. The spatial distribution of high quality and impaired habitats and associated oxygen and total pigment levels also parallels the gradient in watercolumn total nitrogen levels within this estuary. The tidally averaged total nitrogen levels were observed to be 0.33-0.36, 0.39 and 0.45-0.47 mg N L^{-1} within Megansett Harbor, the Channel and Squeteague Harbor, respectively. The relatively low levels of nitrogen are consistent with the generally high quality of eelgrass and benthic animal habitat within this system, but the clear enrichment in the areas losing eelgrass is consistent with the low level of impairment documented for this estuary.

Restoring the impairments to eelgrass and protecting benthic animal habitat is the focus of the nitrogen management threshold analysis (Section VIII.3). As eelgrass within the Megansett /Squeteague Harbor Estuary is critical habitat that structures the productivity and resource quality of the entire system, and it is presently showing moderate impairment, restoration of this resource is the primary target for overall repair of this system. Nutrient management planning for restoration of the eelgrass habitat at the boundary between the Outer and Inner Basins should focus on reducing the level of nitrogen enrichment in basin waters through watershed nitrogen management and managing tidal exchange as appropriate.

Based upon the information above and in Chapter VII and the level of eelgrass impairment observed, it appears that the system is presently only slightly beyond its nitrogen threshold for sustainable eelgrass coverage. This assessment is based upon several factors as follows: 1) the distribution of the remaining eelgrass habitat, 2) the observed loss of eelgrass in the northern and southern eelgrass beds bordering the deep basin of Megansett Harbor, 3) that the decline is slow and relatively recent and 4) that the system is only moderately nitrogen and organic matter enriched.

The absence of eelgrass within the enclosed basin of Squeteague Harbor is consistent with its total pigment (15-20 ug L^{-1}) and total nitrogen (>0.45 mg L^{-1}) levels. The total pigment (mean 11.2-11.8 ug L^{-1}) and total nitrogen (0.358 mg L^{-1}) levels in areas of eelgrass loss are consistent with the pattern of gradual loss overtime as TN concentrations increase. These TN levels and habitat stability/decline are consistent with persistence and loss of eelgrass at similar depths in other estuaries in southeastern Massachusetts.

For example, with the Nantucket Harbor Estuary, tidally averaged levels in the lower reach of Head of the Harbor (0.340-0.353) were associated with recent loss of eelgrass coverage, while eelgrass was lost from West Falmouth Harbor when tidally averaged TN exceeded 0.35 mg L^{-1}. The recent relatively small loss (as a percentage of total coverage) of eelgrass from Quissett Harbor was associated with tidally averaged nitrogen (total nitrogen, TN) levels of 0.354 mg N L^{-1}, while the Outer Basin high quality eelgrass habitat is at lower TN levels, 0.304 mg N L^{-1}. A threshold for tidally averaged TN at the sentinel station in the Inner Basin (QH-2) in Quissett Harbor of 0.34 mg was selected to restore eelgrass habitat.

For Megansett Harbor a threshold for tidally averaged TN at the sentinel station (MG-2, Figure VI-1) of 0.35 mg N L^{-1} was selected to restore eelgrass habitat based upon the depth and TN levels within the stable eelgrass beds. This threshold is similar to that which was developed for West Falmouth Harbor and Phinneys Harbor, and is focused in part on restoring eelgrass where it had persisted until recently. In addition, lowering the level of nitrogen enrichment at the sentinel station will lower nitrogen levels throughout the estuary (Section VIII.3) with the parallel effect of protecting and improving infaunal habitats in the inner reaches of Squeteague Harbor. Therefore, the goal is to achieve the nitrogen target at the sentinel location and restore the historical eelgrass habitat within Megansett Harbor, resulting also in the protection and improvement of infaunal habitat throughout the System. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations are discussed in Section VIII.3, below.

VIII.3 DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous sections were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass in the Megansett Harbor system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels at station MG2 reached the threshold level of 0.35 mg/L set for the 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. A comparison between septic loadings for present and threshold modeling scenarios is provided in Tables VIII-2. A comparison between total present watershed load and the threshold loading scenario is presented in Table VIII-3.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required approximately 20% 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 25% of the septic load from the main Megansett Harbor watershed (including Rands Harbor and Fiddlers Cove) results in a 17% reduction in total watershed nitrogen load. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent ‘worst-case’ summertime conditions. The benthic flux for this modeling effort is reduced from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in outer Megansett Harbor, as discussed in Section VI.2.6.1.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN concentrations of between 11% and 22% is required in the system, between the main harbor basin and the inner reaches of Squeteague Harbor.

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

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

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the Megansett 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 load (kg/day)	threshold load (kg/day)	threshold % change
Megansett Harbor	12.871	9.653	-25.0%
Megansett Channel	2.764	2.488	-10.0%
Squeteague Harbor	5.216	4.695	-10.0%
System Total	20.852	16.836	-19.3%

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 Megansett 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
Megansett Harbor	18.978	15.760	-17.0%
Megansett Channel	3.699	3.422	-7.5%
Squeteague Harbor	9.263	8.741	-5.6%
System Total	31.940	27.924	-12.6%

Table VIII-4. Threshold sub-embayment loads used for total nitrogen modeling of the Megansett 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)
Megansett Harbor	15.760	5.556	-23.545
Megansett Channel	3.422	0.386	-0.669
Squeteague Harbor	8.741	1.000	0.146
System Total	27.924	6.942	-24.068

Table VIII-5. Comparison of model average total N concentrations from present loading and the **threshold scenario**, with percent change over background in Outer Megansett Harbor (0.329 mg/L), for the Megansett Harbor system. The threshold sentinel station (MG2) is presented in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Inner Megansett Harbor	MG1	0.387	0.379	-14.9%
Outer Megansett Harbor	**MG2**	**0.355**	**0.349**	**-22.1%**
Outer Megansett Harbor	MG3	0.346	0.342	-21.7%
Outer Megansett Harbor	MG4	0.330	0.330	-20.0%
Megansett Harbor Channel	SQ1	0.413	0.402	-12.9%
Inner Squeteague Harbor	SQ2	0.448	0.435	-11.4%

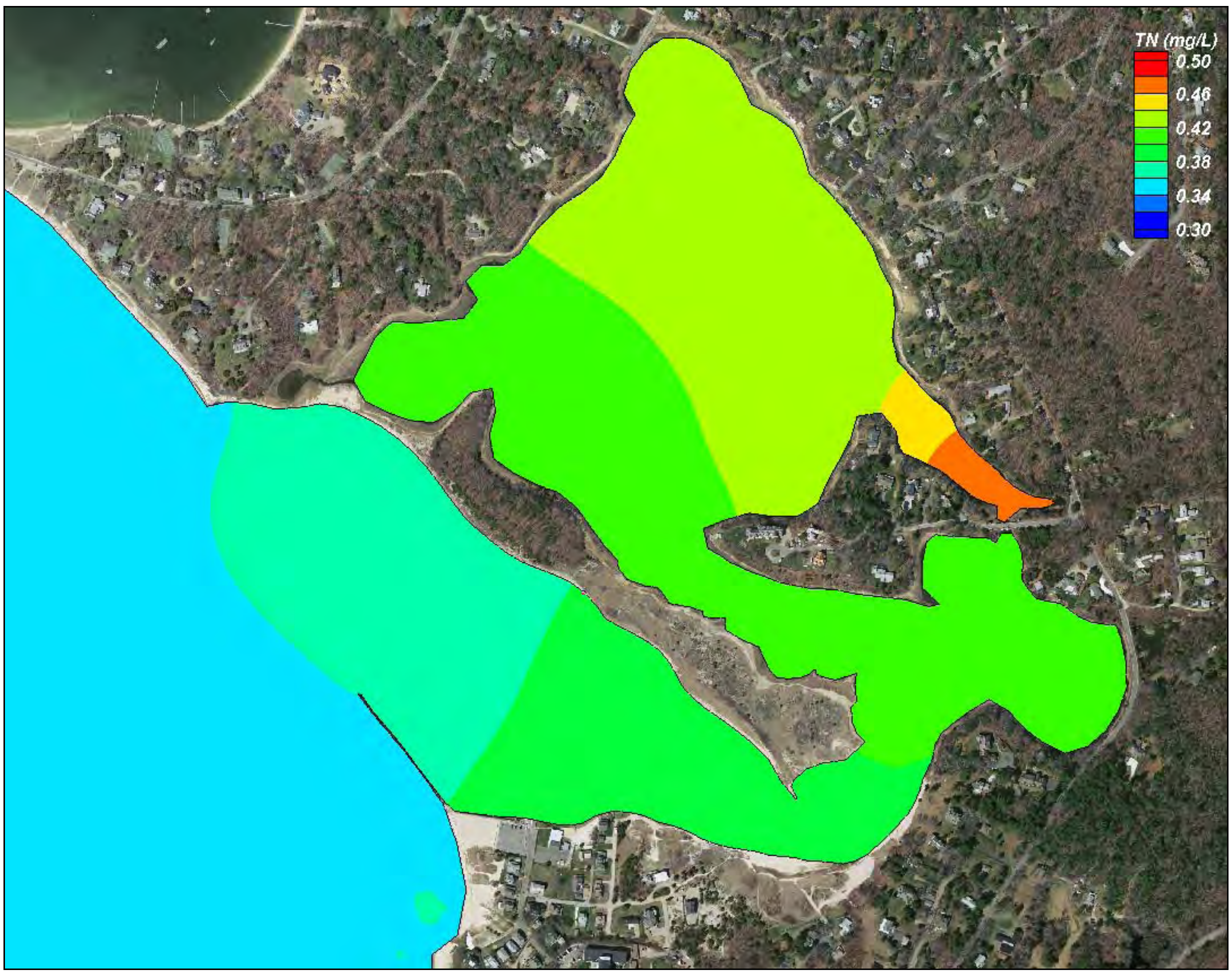


Figure VIII-1. Contour plot of tidally averaged modeled total nitrogen concentrations (mg/L) in the Megansett Harbor system, for threshold loading conditions.

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