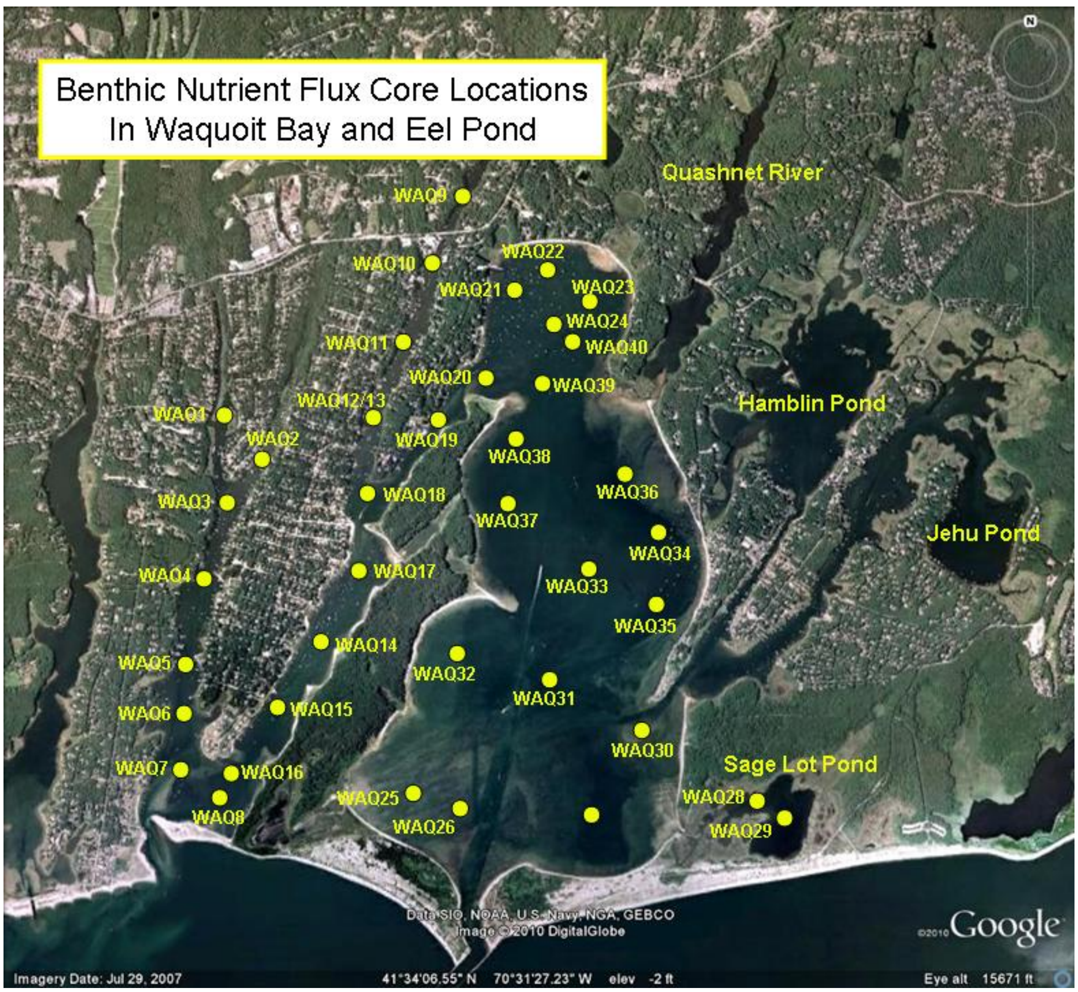
Massachusetts Estuaries Project

Linked Watershed-Embayment Approach to Determine Critical Nitrogen Loading Thresholds for the Waquoit Bay and Eel Pond Embayment System Towns of Falmouth and Mashpee, Massachusetts



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FINAL REPORT – MARCH 2013

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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 Waquoit Bay embayment system, a coastal embayment within the Towns of Falmouth and Mashpee, Massachusetts. Analyses of the Waquoit Bay embayment system (inclusive of the Eel Pond, Childs River, Quashnet River, Hamblin Pond, Jehu Pond and Sage Lot Pond sub-embayments) was performed to assist the Towns of Falmouth and Mashpee with up-coming nitrogen management decisions associated with the current and future wastewater planning efforts of the Towns, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and inlet maintenance programs. As part of the MEP approach, habitat assessment was conducted on the embayment based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Towns of Falmouth and Mashpee 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 Waquoit Bay embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Towns) for the restoration of the Waquoit Bay embayment system.

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

The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the culture, economy, and tax base of Massachusetts's coastal communities. The primary nutrient causing the increasing impairment of our coastal embayments is nitrogen, with its primary sources being wastewater disposal, and nonpoint source runoff that carries nitrogen (e.g. 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 Waquoit Bay embayment system within the Towns of Falmouth and Mashpee is showing signs 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 Towns of Falmouth and Mashpee have recognized the severity of the problem of eutrophication and the need for watershed nutrient management. The Town of Falmouth is currently developing a Comprehensive Wastewater Management Plan which the Town plans to implement upon its completion. The Town of Falmouth has also been working with the Town of Mashpee that has also completed and implemented wastewater planning in the portions of Waquoit Bay watershed that exist within the Town of Mashpee. In this manner, this analysis of the Waquoit Bay system is yielding results which can be utilized by the Town of Falmouth along with MEP results developed for the other estuaries of the town (specifically, Rands Harbor, Fiddlers Cove, Wild Harbor, West Falmouth Harbor, Quissett Harbor, Little Pond, Falmouth Inner Harbor, Oyster Pond, Great Pond, Green Pond, Bournes Pond and Eel Pond/Childs River) in order to give the Towns of Falmouth and Mashpee the necessary results to plan out and implement a unified town-wide approach to nutrient management. The Towns of Falmouth and Mashpee with associated working groups have recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making and alternatives analysis. The completion of this multi-step process has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, which is a partnership effort between all MEP collaborators and the Towns. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns' nutrient management groups to predict the impacts on water quality from a variety of proposed management scenarios.

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

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

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

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

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

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

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

Application of MEP Approach: The Linked Model was applied to the Waquoit Bay embayment system by using site-specific data collected by the MEP and water quality data collected by both the Waquoit Bay National Estuarine Research Reserve and a joint effort comprised of water sampling undertaken by the Town of Mashpee with the Coastal Systems Program at SMAST-UMD (see Section II for full explanation). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Falmouth Planning Department, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Waquoit Bay embayment system and the systems sub-embayments as appropriate (current and build-out loads are summarized in Table IV-3). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamic characteristics of the system were 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 Waquoit Bay embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Vineyard Sound source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Waquoit Bay embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the 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 chlorophyll-*a* were also considered in the assessment.

The nitrogen thresholds developed in Section VIII-2 were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Waquoit Bay 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 Waquoit Bay system. It is important to note that load reductions can be produced by reduction of any or all sources, increasing embayment flushing or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions developed in Section VIII represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Waquoit Bay embayment system shared between Towns of Falmouth and Mashpee. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. For Illustrative purposes, the MEP analysis has initially focused upon nitrogen loads from on-site septic systems as a test of the potential for achieving the level of total nitrogen reduction for restoration of the embayment system. The concept was that since nitrogen loads associated with wastewater generally represent 60% - 85% of the controllable watershed load to the Waquoit Bay embayment system and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through this source is a good gauge of the feasibility for restoration of these systems.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Waquoit Bay embayment system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure. At present the overall Waquoit Bay Embayment system (comprised of: Waquoit Bay, Eel Pond, Childs River, Quashnet River, Sage Lot Pond, Hamblin Pond/Little River and Jehu Pond/Great River) is generally showing impaired habitat quality resulting from nitrogen enrichment (Section VII, Table VIII-1). This indicates that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system. In general, the habitat quality within the basins of this System is manifested by the temporal changes in eelgrass coverage and benthic community characteristics, which are consistent with the observed levels of nitrogen and organic matter enrichment and magnitude of oxygen depletion, as well as the sediment characteristics and general absence to only sparse macroalgal accumulations. The distribution and levels of habitat impairment within the Waquoit Bay Embayment System is consistent with the moderate to significant level of nitrogen enrichment. The near complete loss of the extensive eelgrass beds within the Waquoit Bay Embayment System makes restoration of this resource the primary focus for nitrogen management, with the associated goal of restoring impaired benthic habitat in areas of the system (all subembayments) showing clear signs of impaired benthic communities.

Determining the nitrogen target to restoring these habitats is the focus of the nitrogen management threshold analysis provided in Section VIII.

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

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a levels within the main Basin (north and south) of Waquoit Bay indicate high levels of nutrient enrichment and impaired habitat quality. The oxygen data are consistent with high organic matter loads and the moderate levels of phytoplankton biomass (chlorophyll-a levels) indicative of nitrogen enrichment of this estuarine basin. The large daily excursions in oxygen concentration in the main basin of Waquoit Bay combined with the clear evidence of oxygen levels above atmospheric equilibration throughout Waquoit Bay and its sub-embayments is further evidence of nitrogen enrichment at a level consistent with habitat degradation. Oxygen conditions within the northern portion of the main basin of Waquoit Bay showed low to moderate levels of oxygen depletion consistent with the organically enriched sediments, moderate levels of phytoplankton biomass and generally low macroalgal accumulations associated with its observed level of nitrogen enrichment. The southern portion of the main basin of Waquoit Bay is also showing moderate (to high under algae mat) oxygen stress to benthic communities, with a gradient of less oxygen depletion moving toward the tidal inlet. The bottom waters have large daily excursions in oxygen levels (5-7 mg L^{-1}), more pronounced than in the northern portion. Large daily excursions in oxygen levels are a clear indication of organic enrichment resulting from nitrogen loading and, within the main basin, manifests itself through organic enrichment of sediments, large macroalgal accumulations and phytoplankton biomass. Chlorophyll-a levels paralleled the oxygen levels within the southern portion of Waquoit Bay. The mid region generally shows only moderately enhanced water column chlorophyll, averaging 7 ug L^{-1} and exceeded 5 and 10 ug L^{-1} for 89% and 6% of the time-series record, respectively. Slightly lower levels were found near the inlet, with chlorophyll values averaging 5.4 ug L^{-1} and exceeded 5 and 10 ug L^{-1} 56% and 2% of the time-series record, respectively. It should be noted that conditions at the "inlet" location are the highest quality within the main basin of Waquoit Bay.

The western sub-embayments to the Waquoit Bay Embayment System, Eel Pond and Childs River, exhibit significant summer time oxygen depletion. The upper reaches within Eel Pond and the main channel of the Childs River have significant and frequent oxygen depletion of bottom waters, while the basin of Eel Pond adjacent the tidal inlet shows only moderate levels of oxygen depletion, due to the direct influence of the high quality floodwaters from Vineyard Sound. The lower basin is strongly influenced by the nutrient and organic enriched low oxygen waters entering from the upper tidal reaches during out-flowing ebb tides. However, the high turnover of water in lower Eel Pond reduces its ability to build up nutrients, phytoplankton biomass and organic matter, while the inflow of high quality floodwaters from Vineyard Sound results in relatively high water quality for a portion of the flood tide period. The upper portions of the western branch of Eel Pond and the Childs River are clearly presenting significant oxygen stress to benthic animals, while the lower Eel Pond basin presently has a lower level of oxygen stress. The spatial pattern of oxygen stress parallels chlorophyll-a, indicative of underlying nitrogen enrichment as the ultimate cause of the extent of oxygen depletion. Within the upper portion of Eel Pond and the Childs River, where significant oxygen depletion was observed, chlorophyll-a levels were very high over the entire study period. In addition, both the upper portion of Eel Pond and the Childs River have regions with accumulations of macroalgae which further contribute to the organic enrichment and enhance bottom water oxygen depletion and further impair benthic animal habitat.

The dissolved oxygen records for the tidally influenced lower Quashnet River and the upper region of Hamblin Pond indicate that these sub-embayments currently maintain a high and moderate level of oxygen stress, respectively. Jehu Pond showed a high level of oxygen depletion, at a level which will impair habitat quality, with dissolved oxygen levels periodically approaching anoxia. Based upon measured total chlorophyll-a pigments (sum of chlorophyll-a and its immediate breakdown product, pheophythin a, as a better indicator of bloom conditions) it is clear that the Quashnet River is highly eutrophic with total chlorophyll-a levels in the upper and mid regions averaging >20 ug L^{-1}. Jehu and Hamblin Ponds support moderate to high total chlorophyll levels, averaging 11.9 and 7.4 ug L^{-1}, respectively. Jehu Pond appears to be showing more nutrient enrichment than Hamblin Pond, both on average and relative to the size of the blooms. The high phytoplankton biomass in Jehu Pond is consistent with the observation of oxygen stress in this system. The moderate total chlorophyll levels in Hamblin Pond are consistent with its moderately good oxygen status. Similarly, Little River and Great River had average total chlorophyll levels of 5-6 ug L^{-1}, as might be expected from the outflow concentrations from their upper basins. The agreement between the chlorophyll land oxygen levels in these Pond basins is likely the result of their physical structure.

Eelgrass surveys and analysis of historical data for the Waquoit Bay Embayment System indicated that eelgrass beds, when the watershed was relatively undeveloped (1951), were generally found within each sub-embayment, with the exception of Quashnet River and the uppermost portion of the western branch of Eel Pond. Multiple lines of evidence clearly indicated that the main basin of Waquoit Bay historically supported significant eelgrass coverage, primarily in the northern basin (large fringing beds) and in the region of the tidal inlet, although there is no evidence of coverage in central region of the lower main basin over the past 60 years. Similarly, within the western sub-embayments significant eelgrass coverage has been documented for the lower Childs River and the east branch and lower basin of Eel Pond, with no historic documented beds in the west branch. It should be noted that given the configuration of the Childs River, it is likely that the historic beds were primarily confined to the shallower margins rather than filling the basin. In contrast, presently virtually all eelgrass has been lost from the Waquoit Bay Embayment System, with the exception of Sage Lot Pond and a possible remnant patch associated with the main tidal inlet to Waquoit Bay. All of the basins with well documented historic eelgrass coverage within this system, which no longer support eelgrass coverage, are classified as significantly impaired relative to eelgrass habitat by the protocols of the MEP. The present levels of nitrogen, chlorophyll, periodic oxygen depletion and accumulations of macroalgae support that nitrogen enrichment is the primary mechanism of eelgrass decline in these basins.

The near complete loss of the extensive eelgrass beds within the Waquoit Bay Embayment System has paralleled the increase in watershed development and the associated nitrogen enrichment to the System's estuarine waters. It appears that as the component sub-embayments became nutrient enriched, they could no longer support eelgrass beds. The proximate cause of loss is most likely related to nutrient related shifts in habitat quality, most significantly increased phytoplankton biomass as seen by high chlorophyll-a (turbidity/shading), resulting in decreased light penetration through the water column. However, it is likely that if nitrogen loading were to decrease, eelgrass could be restored in these basins to the 1951 pattern. This is supported by the fact that small areas still remain and that the decline from “full” coverage has been relatively recent.

Benthic animal indicators were consistent with the levels of oxygen depletion, chlorophyll-a and organic enrichment, including macroalgal accumulation, within all of the sub-embayments of the Waquoit Bay System. The System is presently supporting benthic habitat ranging from minimally/moderately impaired to significantly impaired. It should be noted that, given the loss of eelgrass beds, throughout the main basin of Waquoit Bay, eastern and lower Eel Pond (fringing beds in Childs River), as well as the Quashnet River, Hamblin Pond/Little River and Jehu Pond/Great River, it is clear that the Waquoit Bay Embayment System is clearly impaired by nutrient overloading throughout its tidal reaches. Based upon the infaunal community survey it appears that most of the Waquoit Bay Embayment System is presently supporting impaired benthic animal habitat, primarily resulting from nitrogen and organic enrichment, periodic oxygen stress and in some areas, accumulations of drift macroalgae that "smother" benthic animals. At present, high quality benthic habitat is only found within the lower basin of Eel Pond and the Seapit River. These areas do not have significant accumulations of macroalgae or oxygen depletion and have relatively oxidized sediments comprised of medium to fine sands with low organic enrichment or consolidated muds.

Overall, the pattern of infaunal habitat quality throughout the Waquoit Bay Embayment System is consistent with measured dissolved oxygen concentrations, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily includes the structure of the specific estuarine basin, specifically as to whether a basin area is wetland influenced or an open water tidal embayment. Based upon this analysis it is clear that most of the benthic animal habitat within the Waquoit Bay Embayment System is moderately to significantly impaired (Quashnet River, severely degraded) by nitrogen and organic matter enrichment, while the moderate to high quality benthic animal habitat is primarily found in the region of the Seapit River down to the Eel Pond inlet. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the significantly impaired basins presently range from 0.65 to 1.20 mg TN L^{-1}, levels typical of other estuarine basins with significant impairment of benthic animal habitat throughout southeastern Massachusetts estuaries.

3. Conclusions of the Analysis

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

Threshold nitrogen levels for this embayment system were developed to restore or maintain SA waters or high habitat quality. In this system, high habitat quality was defined as supportive of eelgrass and supportive of diverse benthic animal communities. Dissolved oxygen and chlorophyll-*a* were also considered in the assessment.

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Town of Falmouth and Mashpee Waquoit Bay embayment system was comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 60% - 85% of the controllable watershed nitrogen load to the embayment was from wastewater.

A major finding of the MEP clearly indicates that a single total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of the Great, Green and

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

The threshold nitrogen levels for the Waquoit Bay embayment system, shared by Falmouth and Mashpee, were determined as follows:

Waquoit Bay Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Waquoit Bay Embayment system should reflect both recent pre-degradation habitat quality and be reasonably achievable. The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout and embayment system, is to identify a sentinel location within the embayment or sub-embayment and second, to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality. Given the complex configuration and hydrodynamics of the Waquoit Bay Embayment System, multiple nitrogen thresholds locations were selected as to insure an accurate determination of estuarine response to reductions in watershed nitrogen loading and/or enhanced tidal flushing.

- Within the main basin of Waquoit Bay, a sentinel station was selected at the long-term monitoring location (WB12) targeting restoration of eelgrass habitat within the basins northern and southern portions. Similarly, within the Childs River the long term monitoring within the main channel near the upper extent of the historic coverage as selected (CR02). Meeting the nitrogen target at both these stations will necessarily result in lower total nitrogen levels in the down gradient Eel Pond (east branch and Eel Pond lower basin) and southern portion of Waquoit Bay, to restore eelgrass habitat in these lower tidal reaches as well. Meeting the nitrogen threshold in upper Waquoit Bay will also lower nitrogen related impairments in Sage Lot Pond, which is presently supporting moderately impaired eelgrass habitat. As such, Sage Lot Pond is presently just over its nitrogen threshold, and only a moderate reduction in nitrogen levels is required to achieve restoration. Since Sage Lot Pond exchanges tidal waters with the lower portion of Waquoit Bay, as nitrogen levels are reduced in the main basin, Sage Lot Pond levels will decline as well. For these basins, the target nitrogen level to achieve restoration of eelgrass habitat is 0.38 mg TN L^{-1}, compared to the present tidally averaged TN levels of 0.40 mg TN $L^{-1}$for Waquoit Bay and 0.63 mg TN $L^{-1}$for the Childs River station

- Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fisheries resources), benthic infaunal habitat quality must also be supported as a secondary condition. This is the case for the western basin of Eel Pond which has not historically supported eelgrass beds, but presently has significantly impaired benthic animal habitat (and the Quashnet River). Benthic animals are more tolerant of nutrient and organic matter enrichment than eelgrass, which requires clear waters and high oxygen levels. At present, in the regions with moderately to significantly impaired infaunal habitat within upper Eel Pond, long term monitoring station ER01 has an average tidal total nitrogen (TN) level of 0.67 mg TN L^{-1}. The observed impairments throughout this estuary are consistent with observations by the MEP Technical Team in other estuaries along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay). Based upon these observations and findings from MEP analyses completed in other estuaries such as Wareham River and Centerville River, the MEP Technical Team concluded that an upper limit of $\leq$0.50 mg TN L^{-1} tidally averaged TN at the threshold station (ER01) would result in healthy infaunal habitat throughout the western branch of Eel Pond.

- Within the Quashnet River, Hamblin Pond/Little River and Jehu Pond/Great River sub-embayments within the Waquoit Bay System, it was necessary to select 3 sentinel locations. The Quashnet River Estuary operates independent from the Hamblin Pond and Jehu Pond Estuaries, except as they share common source waters from Waquoit Bay. Their interaction is primarily through their effect on the nitrogen level with Waquoit Bay. The sentinel system within the Quashnet River Estuary was set within the upper/mid basin (region above the bridge). Achieving the nitrogen threshold at this station will also improve benthic habitat in the lower basin. Since there is no historical evidence that the Quashnet River Estuary supported eelgrass, the threshold nitrogen concentration was based upon restoring benthic habitat at the sentinel station. The target nitrogen concentration to restore infaunal habitat is based upon the high quality infaunal sites in lower Hamblin Pond and in Little River (Stations 176 and 170, Figure VII-9). The tidally averaged nitrogen levels at these sites are 0.498 and 0.524 mg TN L^{-1}, respectively. These values are consistent with the infaunal guidance levels within the Popponesset Bay sub-embayments of 0.5 to 0.4 mg TN L^{-1} (0.5 mg TN L^{-1}) being the upper threshold value). Based upon these data a conservative estimate for the infaunal threshold for the Quashnet River Estuary is 0.50 mg TN L^{-1}, with 0.52 likely to represent a slight stress, but still high quality habitat.

- Within the Hamblin Pond/Little River and Jehu Pond/Great River Estuaries the sentinel locations were placed within the pond basins. The target nitrogen threshold focuses on eelgrass restoration of these systems. Setting the threshold for these ponds was not straight-forward given that eelgrass was almost completely lost from the main basin of Waquoit Bay prior to significant loss from the Hamblin Pond and Jehu Pond Estuaries in the 1980's. As such, the approach taken by the MEP Technical Team was to develop the threshold nitrogen level for these Ponds in relation to the nitrogen level in the main bay, which serves as the source water (boundary condition) to the ponds. Based upon a main bay boundary condition of 0.38 mg TN L^{-1} (upper eelgrass threshold) the nitrogen levels in the Ponds would necessarily have been >0.38 mg TN L^{-1}, given the gradients established by the interplay of loading and hydrodynamics. This is consistent with the existence of a few diminishing small patches of eelgrass at nitrogen levels on the order of 0.5 mg TN L^{-1} in these ponds in 2001-2003. Based upon the modeling it appears that Jehu Pond could support eelgrass at a nitrogen threshold of 0.446 mg TN L^{-1}. Although Hamblin Pond is similar to Jehu Pond in gross structure, it has very different loading and attenuation characteristics. The result is that the structure of the system produces much lower nitrogen levels so a threshold of 0.38 mg TN L^{-1} was selected to allow for uncertainties.

It is important to note that the analysis of future nitrogen loading to the Waquoit Bay estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that significant increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. Therefore, watershed-estuarine nitrogen management must include management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Waquoit Bay estuarine system is that restoration will necessitate a reduction in the present (2009) nitrogen inputs and management options to negate additional future nitrogen inputs.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Waquoit Bay system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Surface water loads to estuarine waters of the Waquoit Bay system are presented separately from the loads of the sub-embayments to which they discharge.

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 Net Total Load[6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
WAQUOIT BAY SYSTEM										
groundwater sources										
Waquoit Bay	0.422	0.690	1.397	0.000	2.088	11.956	-69.126	-55.082	0.39-0.47	0.38
Childs River - upper	0.485	2.090	9.929	0.000	12.019	0.455	-7.437	5.037	0.89-1.19	0.38
Eel Pond - east branch	0.085	0.482	1.688	0.000	2.170	1.011	26.004	29.185	0.47-0.53	-
Eel Pond - south basin	0.016	0.066	0.458	0.000	0.523	0.663	-5.650	-4.464	0.40	-
Eel Pond - west branch	0.707	3.789	12.548	0.000	16.337	0.890	-4.383	12.845	0.62-0.74	0.50
Quashnet River	0.523	0.868	1.904	0.000	2.773	0.252	11.996	15.020	0.63-0.79	-
Hamblin Pond	0.268	0.953	3.427	0.000	4.381	1.529	7.890	13.799	0.52-0.59	-
Little River	0.027	0.211	0.885	0.000	1.096	0.156	3.439	4.691	0.54	-
Jehu Pond	0.140	1.025	2.888	0.000	3.912	0.674	9.854	14.440	0.58	-
Great River	0.312	0.997	2.674	0.000	3.671	1.307	19.679	24.657	0.59	-
Sage Lot Pond	0.693	1.619	1.132	0.000	2.753	0.471	-3.086	0.139	-	-
surface water sources										
Childs River	0.978	2.485	8.134	0.003	10.622	-	-	10.622	-	-
Quashnet River	4.222	9.641	10.504	0.362	20.507	-	-	20.507	0.52	-
Red Brook	0.449	1.438	6.575	0.000	8.014	-	-	8.014	0.56	-
Waquoit Bay System Total	**9.329**	**24.917**	**57.567**	**0.365**	**90.866**	**19.364**	**-10.821**	**99.409**	**0.39-1.19**	**0.38-0.50**

[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 attenuated wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings (the sum of land use, septic, and WWTF loading)
[5] atmospheric deposition to embayment surface only. Atmospheric loads to surface water inputs are included with their respective watershed load.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 2002 – 20010 data, ranges show the upper to lower regions (highest-lowest) of a sub-embayment.
[8] Eel grass threshold for sentinel site located in Lewis Bay (0.38 mg/L), and infaunal targets at remaining stations.
[a] Surface water discharge to Mill Creek, [b] Surface water discharge to Hyannis Inner Harbor.

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

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
WAQUOIT BAY SYSTEM						
groundwater sources						
Waquoit Bay	2.088	2.088	11.956	-56.779	-42.735	0.0%
Childs River - upper	12.019	4.076	0.455	-4.291	0.240	-66.1%
Eel Pond - east branch	2.170	0.820	1.011	19.480	21.310	-62.2%
Eel Pond - south basin	0.523	0.523	0.663	-4.632	-3.445	0.0%
Eel Pond - west branch	16.337	8.808	0.890	-2.900	6.798	-46.1%
Quashnet River	2.773	1.497	0.252	9.496	11.245	-46.0%
Hamblin Pond	4.381	0.953	1.529	5.712	8.194	-78.2%
Little River	1.096	0.211	0.156	2.554	2.922	-80.7%
Jehu Pond	3.912	1.025	0.674	6.897	8.596	-73.8%
Great River	3.671	0.997	1.307	14.222	16.526	-72.8%
Sage Lot Pond	2.753	1.622	0.471	-2.726	-0.633	-41.1%
surface water sources						
Childs River	10.622	4.115	-	-	4.115	-61.3%
Quashnet River	20.507	13.469	-	-	13.469	-34.3%
Red Brook	8.014	2.096	-	-	2.096	-73.8%
Waquoit Bay System Total	**90.866**	**42.300**	**19.364**	**-12.967**	**48.697**	**-53.4%**

(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 concentrations identified in Table ES-1.
(3) Projected future flux (present rates reduced approximately proportional to watershed load reductions).
(4) Sum of target threshold watershed load, atmospheric deposition load, and benthic flux load.

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The Massachusetts Estuaries Project Technical Team would like to acknowledge the contributions of the many individuals who have worked tirelessly for the restoration and protection of the critical coastal resources in the Waquoit Bay study area. Without these stewards and their efforts, this project would not have been possible. In particular, we would like to recognize and applaud the commitment shown by the Towns of Mashpee, Falmouth, and Sandwich in carrying forward with the Massachusetts Estuaries Project and the restoration of their estuarine systems, and specifically the Waquoit Bay-Eel Pond Embayment System. Significant time and attention has been dedicated to this effort by many town officials most notably Tom Fudala (Mashpee), Jerry Potamis, Amy Lowell Brian Currie, and Bob Shea (Falmouth) and Dave Mason (Sandwich), whose efforts were instrumental to completion of these reports.

Specific recognition is warranted to the significant time and effort developing and implementing a system-wide water quality monitoring program for this estuary, spent by members of the Mashpee Water Quality Monitoring Program and SMAST “volunteers”. These individuals gave of their time to collect nutrient samples from this complex estuary over many years and without this effort the present analysis would not have been possible. The Program is coordinated through the Mashpee Waterways Commission, and has evolved into a partnership between the Mashpee Wampanoag Tribe, the Town of Mashpee and SMAST-UMD, with the Waquoit effort coordinated by Steve Pinard and John West. In addition, data collected by WBNERR through the volunteers of the BayWatcher Program and the SWMP Program were graciously made available and were very useful to this analysis. Freshwater Pond data was provided by the pond surveys conducted by the CCC/SMAST Cape Cod PALS Snapshots and the associated PALS volunteers. Similarly, many staff in the Town of Mashpee worked diligently on this effort, specifically the Mashpee Waterways Commission, Mashpee Shellfish Department (Rick York), Mashpee Watershed Nutrient Management Committee, Mashpee Sewer Commission, and Mashpee Board of Selectman. Thanks also to the Mashpee Water District (Andy Marks) for providing key data and subsequent discussions. Early on, the Mashpee Sewer Commission recognized and supported the present quantitative analysis towards the development of its Comprehensive Nutrient Management Plan to protect/restore Mashpee’s coastal resources.

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I. INTRODUCTION

The Waquoit Bay Estuary, also called the Waquoit Bay-Eel Pond Embayment System (after its major basins), is a complex system comprised of a main bay and associated tributary sub-embayments to both the east and the west. The Quashnet River, Hamblin Pond/Little River, and Jehu Pond/Great River are three major tributary sub-embayments to the Waquoit Bay System and are located along the eastern shore of the main basin. Eel Pond and the Childs River, which are connected to Waquoit Bay by the Seapit River, are large tributary sub-embayments to the Waquoit Bay System and are located along the western shore of the main bay (Figure I-1). The three eastern shore sub-estuaries (Hamblin Pond, Jehu Pond and Quashnet River) were prioritized for initial assessment and threshold analysis by the DEP/SMAST Massachusetts Estuaries Project (MEP) to support on-going nitrogen management planning by the Town of Mashpee. The MEP nutrient threshold analysis for those three sub-embayments was completed in 2004 and the associated MassDEP TMDL has been accepted by USEPA (2007). These eastern basins were compiled in advance of the main basin, as sufficient data existed and there were immediate needs to support watershed planning efforts. Since completion of the initial MEP nutrient thresholds analysis, the required data were collected for analysis of the main basin of Waquoit Bay and its western tributary basins, Eel Pond and Childs River. As such, the previous analysis of Hamblin Pond, Jehu Pond and the Quashnet River systems is being revisited and integrated into the present synthesis and modeling effort. However, as the nutrient thresholds for the eastern embayments remain unchanged, the present effort will not repeat that analysis but refer readers to the prior report (Howes, et al., 2005). Only critical aspects of the prior work required for understanding the present analysis and development of nitrogen thresholds are presented again in this document.

The primary ecological threat to the estuarine resources of Waquoit Bay and its sub-embayments (Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River, Eel Pond, Childs River) is degradation resulting from nitrogen enrichment stemming from nitrogen loading to the watershed. Although the watershed and the Bay have some localized organic contamination and bacterial contamination issues, these do not appear to be having large system-wide impacts. Site-specific organic contamination has been associated with groundwater recharged in the upper watershed, within the Massachusetts Military Reservation (MMR). Documented contaminant plumes enter two of the watershed's major freshwater ponds, Ashumet Pond and Johns Pond, which eventually provide freshwater to the eastern and western sub-embayments of the Waquoit Bay System. The Ashumet Pond plume is mainly secondarily treated wastewater previously discharged to groundwater infiltration beds at the former MMR Wastewater Treatment Facility (e.g., AFCEE, 2000). The John's Pond plume stems from a relatively small input of organic contamination. However, it is unlikely that the organic contaminants associated with Johns Pond have any significant effect on Waquoit Bay, due to the passage through Johns Pond and the mode of transport (surface water flow). It is likely that some fraction of the nitrogen loading from the wastewater plume entering Ashumet Pond does contribute to the overall nitrogen loading to the Waquoit System. However, the MMR has ceased land disposal of treated wastewater within the watershed, improving its treatment system and relocating effluent disposal to beds near the Cape Cod Canal. The portion of the residual plume nitrogen that discharges into the ponds appears to be significantly attenuated by passage through the surface water ecosystem. In addition, the remaining portion of the relict wastewater plume is moving through the Ashumet Valley to Great and Green Ponds in Falmouth, rather than towards the Waquoit System. This nitrogen source was included in the present MEP analysis, as appropriate. This load is a small portion of the overall watershed load.

Figure I-1. Major components of the Waquoit Bay Estuarine System. The study region for the present Massachusetts Estuaries Project analysis is the main open water basin of Waquoit Bay and the two major sub-embayments within the western portion of the system (Eel Pond and Childs River). While the three major sub-embayments within the eastern portion of the Waquoit Bay System (Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River) are integrated in this analysis, they received detailed MEP threshold analysis previously (Howes et al. 2005). Tidal waters from Nantucket Sound enter the main Bay through a single inlet in the barrier beach and a smaller inlet to the Eel Pond sub-embayment. Freshwaters enter the estuary primarily through two major surface water discharges (Childs River to Eel Pond and Quashnet River to the main Bay), several smaller streams (e.g. Red Brook), and direct groundwater discharge.

Bacterial contamination causes closures of shellfish harvest areas periodically within the Bay System. Overall, the Waquoit Bay System is relatively free of bacterial levels requiring management activities, with levels of indicator bacteria exceeding management thresholds only periodically in small areas, generally associated with the smaller tributary systems (Quashnet River, Hamblin Pond, Little River, the head of Eel Pond and the Childs River). However, the mouth of the Moonakis (Quashnet) River is frequently closed to the harvest of shellfish due to bacterial contamination and the Division of Marine Fisheries area associated with Hamblin Pond (DSGA SC16.2) is classified “Prohibited”. This area is located at the northern end of Hamblin Pond near the entry of surface water inflow from Red Brook. In addition, a small area associated with the Little River Boatyard is classified “Conditionally Approved”, closed between May 1 and October 31, as a management precaution related to marina activities. But progress has been made in recent years to reduce bacterial contamination of Bay waters. In 1994, Waquoit Bay was designated a Federal No-Discharge Zone, which mandates that boaters must not discharge wastewaters anywhere within the Bay System. Smaller projects to reduce direct stormwater inflows have also been undertaken, for example improvements associated with the redesigned Meadow Neck Bridge over the mid-lower Quashnet River estuary.

In contrast to bacterial contamination, loading of the critical eutrophying nutrient, nitrogen, to the Bay waters has been greatly increased over the past several decades with further increases certain unless nitrogen management is implemented. The increasing rates of nitrogen loading to the Waquoit Bay Estuarine System, like almost all embayments in southeastern Massachusetts, have resulted from activities associated with a shift in watershed land-use from primarily pine/oak forest to residential development. The largest single nitrogen source associated with this shift is on-site septic system treatment and disposal of domestic wastewater. The Towns of Mashpee and Falmouth have been among the fastest growing towns in the Commonwealth over recent decades and do not have broad sewer service supported by centralized wastewater treatment or significant implementation of distributed nitrogen removing wastewater technologies; although two small facilities (Mashpee High School and Southport) operate within the sub-watershed to the Quashnet River. Within both the eastern and western Waquoit Bay sub-embayment watersheds, wastewater is returned to the aquifer almost entirely through individual on-site septic systems. As continuing increases in watershed nitrogen loading further increase the enrichment of the estuarine waters of this major embayment, water quality declines will continue and accelerate, with further degradation of key estuarine habitats and associated resources.

The primary stakeholders for the Waquoit Bay System are the Towns of Mashpee and Falmouth, while the Town of Sandwich occupies a portion of the upper watershed. These Towns have cooperative agreements relating to the resources of Waquoit Bay, for example shellfish resources are shared (cf. Town of Mashpee Shellfish Regulations 2004). All communities are concerned about documented declines in System health. Initial concerns over habitat quality were followed by major successful efforts of open space protection, most notably South Cape Beach, Washburn Island, and large portions of the Quashnet River watershed. These efforts both preserved habitat areas and reduced the amount of nitrogen likely to be added to Bay waters at watershed full development and thereby significantly lowering nitrogen management infrastructure costs by lowering build-out nitrogen loads. However, these acquisitions do little to restore the presently nitrogen impaired waters of the Waquoit Bay System. Other notable management actions include designation as an Area of Critical Environmental Concern (ACEC) in 1979 and in 1988, admission into NOAA’s National Estuarine Research Reserve program (WBNERR, 1996). At present, the Waquoit Bay National Estuarine Research Reserve is jointly managed by NOAA and the Massachusetts Department of

Conservation Resources (DCR). It should be noted that although there is significant Federal and State presence within the watershed, implementation of nitrogen management strategies for restoration of this system will still primarily fall to the municipalities and local citizens. Therefore, restoration of the impaired reaches of this large estuarine system will require the efforts of citizens and managers primarily within the Towns of Mashpee and Falmouth.

Concern over declining habitat quality within the Waquoit Bay System continues to this day. Periodic macroalgal blooms have caused significant public attention, most recently in the summer of 2003, when massive *Cladophora* accumulations were observed over a large expanse of the nearshore of the northern basin of the main Bay (drift algae). While this "event" was dramatic, it only underscored the extent of nutrient overloading, as macroalgal accumulations have been a serious concern for more than three decades in this system (Curley et al., 1971).

Over the past two to three decades, both primary stakeholder communities (Falmouth and Mashpee) have examined potential management options for the Waquoit Bay System. At present all the towns in the watershed (including Sandwich) are undertaking Comprehensive Wastewater Facilities Planning, targeting restoration of receiving marine waters. The Town of Mashpee is currently conducting planning for the watersheds of the eastern three sub-embayments and for the adjacent Popponesset Bay System. As part of this effort, the Town of Mashpee supported MEP data collection efforts and also supported the collection of the only system-wide nitrogen related water quality data available for this large estuary. The Mashpee Nutrient Monitoring Program has continued through the summer 2010 as well as 2011 (in collaboration with the Wampanoag Tribe. Since it was becoming clear that nitrogen restoration of the Bay would likely require at least some traditional wastewater treatment approaches, the on-going ecological assessment and modeling project was combined with the Town of Mashpee's Watershed Nitrogen Management Plan effort by the Mashpee Sewer Commission early in the last decade. Under the direction of the Mashpee Sewer Commission, the three eastern sub-embayments to Waquoit Bay were included in the first round prioritization of the Massachusetts Estuaries Project to provide state-of-the-art analysis and modeling.

The present MEP effort builds upon the Water Quality Monitoring program and previous hydrodynamic and water quality analyses undertaken to establish the nutrient restoration thresholds for Quashnet River, Hamblin Pond and Jehu Pond. This nutrient threshold analysis for the Waquoit Bay System integrates findings from prior MEP analysis of the three eastern sub-embayments, while also including the two western sub-embayments of Eel Pond and Childs River. Similarly, the analysis includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the main Bay and the western tributary sub-embayments. These critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete watershed nitrogen management planning as well as nitrogen management alternatives development needed by the Towns of Mashpee, Falmouth, and Sandwich. 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 numbers of Town staff, researchers from the Estuarine Reserve and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns of Mashpee, Falmouth, and Sandwich to develop and evaluate the most cost effective nitrogen management alternatives to restore these valuable coastal resources that are currently being degraded by nitrogen overloading.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The nutrient sources 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 their assimilative capacity, the level where nutrients begin to cause declines in ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities. At higher levels, enhanced nutrient 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 a watershed becomes 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 steadily 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 Towns of Falmouth, Mashpee, and Sandwich) are grappling with Comprehensive Wastewater Facilities 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 next 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 other MEP partners 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 MEP approach was selected after extensive review by the MassDEP and USEPA and associated scientists and engineers. It has subsequently been applied to more than 40 estuaries and reviewed by other state agencies, municipalities, non-profit environmental organizations, engineering firms, scientists and private citizens. Over the course of the extensive reviews, the MEP approach has proven to be robust and capable of yielding quantitative results to support management of a wide variety of estuaries.

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 MassDEP and municipalities 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 1) the sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, 2) the allowable load of the pollutant to meet the state water quality standards and 3) the load allocation from all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an outline of an implementation plan.

For this project, MassDEP recognizes that there are likely to be multiple ways to achieve the desired goals/allowable load, some of which are more cost effective than others and therefore, it is extremely important for each Town to further evaluate potential options suitable to their community. As such, MassDEP will likely be recommending that specific activities and timelines be further evaluated and developed by the Towns (sometimes jointly for shared watersheds) through the Comprehensive Wastewater Management Planning process.

The MEP nitrogen threshold analysis includes site-specific habitat assessments and watershed/embayment modeling approaches to develop and assess various nitrogen management alternatives for meeting selected nitrogen goals supportive of restoration/protection of embayment health.

The major MEP nitrogen management goals are to:

- provide technical analysis and supporting documentation to Towns as a basis for sound nutrient management decision-making towards embayment restoration
- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment's model "alive" to address future municipal 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 of more than 40 embayments throughout southeastern Massachusetts as of the date of this report. 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 MEP Technical Team, through SMAST-UMD, has conducted more than 200 scenarios to date.

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 facilitates the evaluation of nitrogen management alternatives relative to meeting water quality targets within a specific embayment. The Linked Watershed-Embayment Model also enables Towns to evaluate improvements in water quality relative to the associated cost. In addition, once a model is fully functional it can be “kept alive” and updated 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 in each component or in multiple components 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 both calibrated and fully field-validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-2). This methodology integrates a variety of field data and models, specifically:

- Water column 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

- dissolved oxygen (DO) record
- Macrophyte survey
- Infaunal survey

I.2 SITE DESCRIPTION

Waquoit Bay and its eastern and western sub-embayments (Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River, Eel Pond and Childs River) are located within the Towns of Falmouth (north & west) and Mashpee (east), on Cape Cod Massachusetts. The southern shore is a barrier beach that separates the Waquoit Bay System from adjacent Nantucket Sound (Figure I-1). At present, each of the three eastern sub-estuaries exchanges tidal waters with the main basin of Waquoit Bay, which receives tidal flows from Nantucket Sound. The main Bay has two main openings to Nantucket Sound, a historically open inlet in the main Bay and an ephemeral inlet that connects Eel Pond (western tributary sub-estuary) to Nantucket Sound. More recently, Hurricane Bob in 1991 created a third inlet immediately east of the Eel Pond entrance; however, this inlet has closed over the past few years. The inlet to the main Bay has been fixed with jetties initially in 1918 (east) and 1937 (west), with subsequent lengthening and enhancements. This inlet has been generally open over the past 50 years. The opening of the second inlet significantly increased the tidal range and flows within the Waquoit Bay System and caused important ecological shifts to its tidal wetlands and possibly other estuarine habitats (Orson and Howes, 1992).

These important “natural” hydrodynamic shifts have been coupled with similarly important anthropogenic alterations within the watershed, including human-induced alterations in flow within the Quashnet River, Hamblin Pond, and Jehu Pond sub-embayments. In those three sub-estuaries geomorphic and hydrologic alterations include the damming of the Quashnet (Moonakis) River to drive mills and alteration of riparian zone for cranberry agriculture, and creation of roadways altering circulation around Monomoscoy Island. Nevertheless, the over-riding watershed change affecting these sub-systems appears to have been the shift from pine/oak forest to farming to current residential land-uses, with its associated large increases in watershed nitrogen loading to the estuarine system.

The Bay’s watershed is primarily distributed among the Towns of Falmouth and Mashpee, with the upper-most portion of the watershed located in Sandwich. Waquoit Bay and both the eastern and western sub-embayments are located in the Mashpee Outwash Plain that supports numerous kettle ponds (Oldale 1992). Eel Pond/Childs River and the Quashnet River sub-estuaries are drowned river valley estuaries resulting from rising sea-level flooding the lower reaches of the valleys formed by groundwater sapping and resulting post-glacial river flows. Today, inflows from the Childs and Quashnet Rivers account for more than 50% of the total freshwater entering the Waquoit Bay/Eel Pond System. In contrast, Hamblin and Jehu Pond appear to be drowned kettle ponds currently exchanging tidal flows with Waquoit Bay through tidal rivers, Little River and Great River, respectively. Both the Hamblin Pond and Jehu Pond sub-systems support significant saltwater wetland resources.

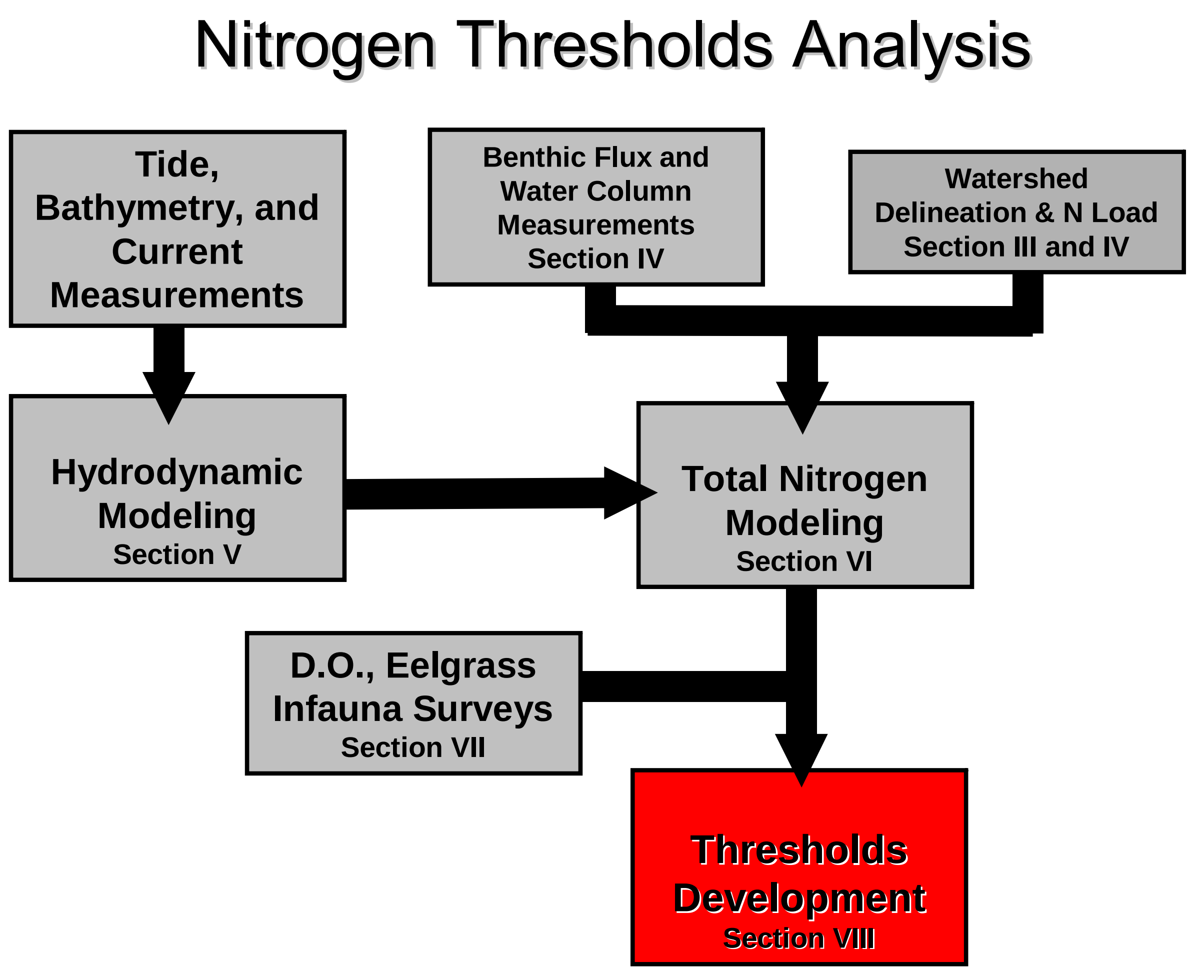


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Note that the approach is not a single model, but a series of models linked by scientists and engineers who validate outputs and inputs to each model.

The tidal reaches of Eel Pond, Childs River and the Quashnet River Estuary are located within the Town of Falmouth while much of the watershed and freshwater reach of the Quashnet River are within the Town of Mashpee. The open water basin of Hamblin Pond is divided between the Towns of Falmouth and Mashpee, while Jehu Pond and Sage Lot Pond are entirely situated within the Town of Mashpee. The subwatersheds to the freshwater Ashumet and Johns Ponds are located within the Town of Sandwich. The Quashnet River is one of the two major surface water inflows to the Waquoit Bay System and originates in John's Pond. The Childs River is a smaller, but significant, surface water inflow of freshwater to the Waquoit Bay system, also originating in Johns Pond. The Childs River flows directly into Eel Pond, which is connected to the main basin of Waquoit Bay via the Seapit River (a tidal cross-connecting channel).

The large number of sub-embayments comprising the Waquoit Bay System greatly increases the System's shoreline and decreases the travel time of groundwater from the watershed recharge areas to bay regions of discharge. The nature of enclosed embayments in populous regions brings two opposing elements to bear: as protected marine shoreline they are popular regions for boating, recreation, and land development; as enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shores. In particular, the Waquoit Bay system and its sub-embayments along the Falmouth and Mashpee shores are at risk of eutrophication from high nitrogen loads in the groundwater and runoff from their watersheds that enter the bay directly or via streamflows. As will be presented in this report, numerous lines of evidence indicate that much of the Waquoit Bay System and its multiple sub-systems (Eel Pond, Childs River, Quashnet River, Hamblin Pond, Jehu Pond) are currently beyond their nitrogen loading threshold and are presently showing various levels of nitrogen related habitat decline.

Within the Waquoit Bay/Eel Pond System, the tidal portions of the eastern and western sub-embayments show clear estuarine characteristics, with extensive salt marsh area, tidal flats and large salinity fluctuations. In contrast, the open water portion of eastern and western portions of the main basin of Waquoit Bay shows more typical characteristics of open water areas, having only fringing salt marshes, relatively stable salinity gradients and a large basin volume relative to tidal prism. Salinities throughout the estuary are generally >28 ppt, indicative of the dominance of tidal inflows, but in the upper reaches of the Childs and Quashnet Rivers with their significant freshwater inflows and enclosed basins, salinities are significantly diluted, 13 ppt and 4-9 ppt, respectively. The tidal forcing for these sub-systems is generated from Nantucket Sound. Nantucket Sound adjacent the inlets in South Cape Beach and the southern shore of Washburn Island, exhibits a moderate to low tide range, with a mean range of about 2.5 ft. Since the water elevation difference between Nantucket Sound and Waquoit Bay is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed into and out of the Bay System during a tidal cycle (note the tide range off Stage Harbor Chatham is ~4.5 ft, Wellfleet Harbor is ~10 ft).

Tidal damping (reduction in tidal amplitude) through an embayment can range from negligible, indicating "well-flushed" conditions, or show tidal attenuation caused by constricted channels and marsh plains, indicating a "restrictive" system where tidal flow and the associated flushing are inhibited. Tidal data indicate only minimal tidal damping through Waquoit Bay inlet. It appears that the tidal inlet is operating efficiently, possibly due to the active inlet maintenance program. Similarly, within the eastern Waquoit Bay System, the tide generally propagates through the main basin and sub-embayments with little attenuation, consistent with relatively unrestricted tidal exchanges. This also appears to be generally the case with Eel Pond and the

Childs River. However the upper portion of the Childs River, above Route 28 does show some signs of tidal damping and the natural inlet of the Quashnet River appears to become periodically occluded by transported sands.

Given the present hydrodynamic characteristics (well flushed) of the Waquoit Bay System, it appears that estuarine habitat quality is more dependent on nutrient loading to bay waters than tidal characteristics within the component sub-embayments. Due to the present hydrodynamics of the main bay and its sub-embayments, habitat degradation appears to be mostly a result of the watershed nutrient inputs that exceed the assimilative capacity of the component basins (i.e. the level of nitrogen input is beyond the natural ability of the bay ecosystems to tolerate them without impairment), not tidal damping.

I.3 NITROGEN LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In sandy glacial outwash aquifers, such as in the watershed to the Waquoit Bay/Eel Pond System, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer minerals (Weiskel and Howes 1992). Since even Cape Cod “rivers” are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems on Cape Cod (DeSimone and Howes, 1998; Weiskel and Howes, 1992; Smith et al., 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant-available nitrogen than phosphorus (relative to plant growth requirements). This export of watershed nitrogen is then paired with the coastal estuary ecosystems, which 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 Waquoit Bay follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

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

Each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation. However, as loading increases a point is reached at which the capacity (termed assimilative capacity) is exceeded, nutrient-related water quality degradation occurs. This point can be termed the “nutrient threshold” and in estuarine management this threshold sets the target nutrient level for restoration or protection. Because 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 is done in the MEP effort). Further, determination of the “allowable N concentration increase” or “threshold nitrogen concentration” used in previous studies had a significant uncertainty due to the lack of 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 total nitrogen concentration throughout the main basin of Waquoit Bay, the western sub-embayments of Eel Pond/Childs River and each of the three eastern sub-embayment to the Waquoit Bay System (monitored by the Mashpee Water Quality Monitoring Program) with site-specific habitat quality data (dissolved oxygen, eelgrass, phytoplankton blooms, benthic animals). The integration of site-specific nitrogen data with site-specific habitat quality data allows the MEP to “tune” general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, almost all of the estuarine reaches within the Waquoit Bay System are near or beyond their ability to assimilate additional nutrients without impacting their ecological health. Nitrogen levels are elevated throughout the System and eelgrass coverage has declined significantly over the past 60 years in the main basin of Waquoit Bay as well as the Eel Pond, Hamblin Pond and Jehu Pond sub-estuaries (Short and Burdick, 1996). Eelgrass has not historically been observed in either the Quashnet River sub-embayment or the Eel Pond/Childs River sub-embayment. Loss of eelgrass has been followed by documented accumulations of drift macroalgae that further degrade benthic animal habitat and reduce food sources for fish and avian fauna. Macroalgal accumulations have been well documented in several basins of this estuarine complex over the past 40 years (Curley et al., 1971, Valiela et al., 1992). The result is that nitrogen management for Waquoit Bay and its sub-embayments covered in this MEP Report must focus on restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed “eutrophication” and when the nutrient loading is primarily from human activities, it is specified as “cultural eutrophication”. Although the influence of human-induced changes has increased nitrogen loading to the systems and contributed to the degradation in ecological health, it is possible that eutrophication within Waquoit Bay and its sub-embayments could potentially occur without man’s influence and must be considered in the nutrient threshold analysis. While this finding would not change the need for restoration, it would change the approach and potential targets for management. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a “pristine” system.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” for water quality modeling of Waquoit Bay and the eastern/western Waquoit Bay sub-embayment systems; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within each 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 overall Waquoit Bay system inclusive of the eastern and western sub-embayments that are hydrodynamically connected to the main basin of Waquoit Bay System. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Bay as a whole as well as each of the sub-systems. Once the hydrodynamic properties of each component of estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen throughout the entire system at current and build-out loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations by USGS using a modification of the West Cape groundwater model for sub-watershed areas designated by MEP. Almost all nitrogen entering Waquoit Bay is transported by freshwater, both from the rivers and directly from groundwater. Concentrations of total nitrogen and salinity of Nantucket Sound source waters and throughout the Waquoit Bay System were taken from the Mashpee Water Quality Monitoring Program (supported by the Town of Mashpee and Mashpee Wampanoag Tribe in association with the Coastal Systems Program at SMAST). Measurements of nitrogen and salinity distributions throughout estuarine waters of the System were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Waquoit Bay System inclusive of the east and west sub-embayments of the Towns of Falmouth, Mashpee, and Sandwich. 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 Towns of Falmouth, Mashpee, and Sandwich data and offshore water column nitrogen values were derived from an analysis of monitoring stations in Nantucket Sound (Sections IV and VI). 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 the entire system and its component sub-embayments was performed that included a review of existing water quality information and the results of a benthic analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed (Section VIII) for restoration of the over-all Waquoit Bay System. Section VIII typically includes an example load-reducing scenario to meet the threshold levels. This example assessment represents only one of many solutions and is produced to assist the Towns in developing a variety of alternative nitrogen management options for this system. The results of the nitrogen modeling for each scenario have been presented in Section VIII with references provided 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 that lead to reduced water clarity, organic matter enrichment of waters and sediments and concomitant increases in rates of oxygen consumption. Periodic depletion of dissolved oxygen, especially in bottom waters, and the limitation of the growth of desirable species such as eelgrass ultimately result from these assaults on the aquatic system. Even without changes to water clarity and bottom water dissolved oxygen, the increased organic matter deposition to the sediments generally results in a decline in habitat quality for benthic infaunal communities (animals living in the sediments). This habitat change causes a shift in infaunal communities from high diversity deep burrowing forms (which include economically important species), to low diversity shallow dwelling organisms. This shift alone causes significant degradation of the resource and a loss of productivity to both the local shell fisherman and to the sport-fishery and offshore fin-fishery, both of which are dependant upon these highly productive estuarine systems as habitat and a food resource during migration or different phases of organism life cycles. This 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 Waquoit Bay and its associated tributary sub-embayments (Eel Pond, Childs River, Quashnet River, Hamblin Pond, and Jehu Pond) that are the focus of this nutrient threshold analysis, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. This approach has been formalized through the development of tools for predicting nitrogen loads from watersheds and the concentrations of water column nitrogen that may result. Additional development of the approach generated specific guidelines as to what is to be considered acceptable water column nitrogen concentrations to achieve desired water quality goals (e.g., see Cape Cod Commission, 1991, 1998; Howes et al., 2002).

Many of the previously developed tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specific characteristics of a given water body. The present Massachusetts Estuaries Project (MEP) study focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species. The linked watershed-embayment approach is built using embayment specific measurements, thereby enabling calibration of the prediction process for specific conditions in each of the coastal embayments of southeastern Massachusetts, including the component sub-embayments to the Waquoit Bay System (Waquoit Bay, Quashnet River, Hamblin Pond, Jehu Pond, Eel Pond and Childs River sub-estuaries).

Waquoit Bay and the eastern tributary sub-embayments to Waquoit Bay are part of the Waquoit Bay National Estuarine Research Reserve (WBNERR). The National Estuarine Research Reserve System (NERR) was established to select “representative” estuarine systems associated with the coastal waters of the United States to support research and long-term monitoring of estuarine change. WBNERR joined the National Reserve System in 1988. Over the intervening ~25 years, research has been conducted on organisms, land-use, and effects of nitrogen on embayment habitats. In addition, a land-use nitrogen loading model was developed to assess watershed nitrogen loading rates. The various scientific publications and appropriate technical reports that have been produced were reviewed as part of the MEP assessment to garner quantitative data and qualitative information of use to the present data collection, synthesis, assessment, and modeling effort. As part of the present MEP analysis of the Waquoit Bay System, the MEP Technical Team is integrating prior findings from the MEP Threshold Analysis of the Quashnet River, Hamblin Pond and Jehu Pond. Additionally, the MEP Technical Team, as part of this system-wide analysis is including site-specific information of the main basin of Waquoit Bay and the western tributary sub-embayments, Eel Pond and the Childs River. Inclusion of these two tributary systems was necessary as they are hydrodynamically connected to the main basin of Waquoit Bay and combined with the other sub-embayments form the greater estuarine complex that is the Waquoit Bay Embayment System. A brief review of previous studies that relate to and were utilized in the MEP analysis is given below.

Data collected by Curley et al. (1971) indicate that as far back as the late 1960's, there was evidence of nutrient related habitat decline within the eastern region of the Waquoit Bay System. This was confirmed and expanded upon two decades later in the first major scientific publication related to nutrient conditions in the eastern Waquoit Bay System (Valiela et al., 1990). This latter study documented eelgrass decline occurring within the Bay and its tributary systems, shifts in benthic species, and concluded that the underlying cause was increasing nitrogen loading from the associated watersheds. Further investigations supported the detrimental effects of increased nitrogen on eelgrass (Valiela et al., 1992, Short and Burdick, 1996), enhancement of macroalgal accumulations (Hauxwell et al., 1998, Thompson and Valiela, 1999), system respiration (D'Avanzo et al., 1996), and potential moderate shifts in fish abundance and growth (Tober et al., 2000).

Coupled to these investigations of biological response to nitrogen loading has been an attempt to determine watershed nitrogen loading rates. This approach has been termed the Waquoit Bay Nitrogen Loading Model (Valiela et al., 1992, Valiela et al., 2000). This approach is aimed at producing a research model which tracks nitrogen from all sources and uptake within the watershed, and attempts to predict the nitrogen discharges to the estuary. The approach is similar in construct to other land-use loading models including the MEP watershed module. The major difference between this land-use model and most others used in watersheds with sandy outwash aquifers is in regards to the attenuation of nitrogen during transport through the aerobic aquifer soils. Uptake of nitrogen is commonly observed in surface water systems where biological cycling of nitrogen results in a portion of the nitrogen being lost due to denitrification. However, a multitude of researchers studying nitrogen transformations in aerobic sandy outwash aquifers have concluded that nitrogen attenuation is generally negligible in these situations. Watershed nitrogen loading models developed by the USGS, CCC, Buzzards Bay Project and the MEP are based upon these results. Further, validation of the various factors employed in the Waquoit Bay Nitrogen Loading Model is not always clear from available information, although some factors are well developed and nearly identical to other watershed models. However, it has not always been possible to rectify differences in watershed areas, nitrogen loads, and freshwater discharge volumes from the various reports and papers. More importantly, validation of the model was based upon groundwater well point measurements, which sampled only a small portion of the full cross-section of the groundwater discharge boundary. Since no fractionation of the groundwater nitrogen pool or any salinity data was presented, it is not possible to evaluate whether the sampling at the "high tide mark at the seepage face" is representative of the groundwater flow. Limitations in this approach to measurement of groundwater nitrogen discharges are underscored by the very large discrepancy in the Sage Lot Pond sub-system which receives little anthropogenic loading (modeled versus measured from Valiela et al., 2000, Table 2, 147 versus 846 kg N yr^{-1}, respectively). In addition, the "measured" loads to Hamblin Pond, Jehu Pond, and Quashnet

River using the watershed areas presented in Valiela et al., 2000 yield agreements to modeled loading of 54%, 73% and 118% respectively (see Table 2 in Valiela et al., 2000). Based on a general review of the Waquoit Bay Nitrogen Loading Model results published to date, there appeared to be significant bias in the model at higher nitrogen mass loadings. However, this research model was a unique attempt to capture all of the sources of transformations of nitrogen during passage through each major element of the soil system (biotic surface layer, vadose zone and aquifer) for each of the land-use types. It clearly fulfilled a critical role as a research model in indicating areas to direct additional future studies (e.g. aquifer attenuation, validation approaches). It should be noted that the model stops at the freshwater/salt water interface, and does not include the estuary itself (just the watershed).

In addition to the concerns noted above, comparison of the prior watershed modeling results to the MEP loads (Section IV) is not straightforward. Most importantly, the watershed area found by the MEP/USGS watershed delineation effort, based on an updated groundwater model and improved parameterization as described in Chapter IV, differs from the watershed delineation used in the research modeling efforts in the early 1990's. It should be noted that the modeled Quashnet River Watershed nitrogen load is based upon freshwater discharges. In the earlier work, Quashnet River watershed total freshwater discharge was calculated from watershed area and recharge and compared to measured discharges (Valiela et al., 1992). The two estimates differed by only ~13%. Examination of the USGS discharge data during the likely period of this study (1989-1992) showed annual total river discharges of 1.17 to 1.32 10^7 m^3 yr^{-1}, compared to 1.1 10^7 m^3 yr^{-1} in the study, indicating excellent agreement. This river discharge was estimated to account for >80% of the total freshwater discharge from the Quashnet watershed. However, the 2657 ha watershed area upon which the freshwater flow values were based is ~30% larger than the watershed upon which the nitrogen loading comparison is based, 2055 ha (Valiela, et al., 1992). Interestingly, the USEPA in evaluating the Waquoit Bay nitrogen loading relied upon the "measured" nitrogen inputs from the well point samplers and the estimated groundwater discharges (see Figure II-1 in USEPA, 2002). It is likely that these estimates will change significantly given the shift in watershed delineations (hence watershed area) and recent improvements in the USGS's groundwater recharge estimates.

A more recent approach to evaluate nitrogen levels in Waquoit Bay and subsequent impacts on the Bay in response to watershed nitrogen loading has also been proposed (USEPA, 2002). This approach is not suited for the evaluation of nitrogen management alternatives at this time, as the approach is not robust, is calibrated to inorganic nitrogen concentrations (which generally represent a small fraction of the total nitrogen pool), and does not account for circulation or dispersion of nitrogen within the receiving waters.

Based upon the above concerns and shortcomings related to previous nitrogen loading estimates, and especially the new USGS watershed delineations, the MEP Technical Team was not able to directly assimilate these previous watershed nitrogen loading estimates. However, the various key source factors that were well documented as well as the habitat data were integrated into the MEP effort. Comparison to previous nitrogen loading studies has focused primarily on the watershed delineation aspects.

Hydrodynamic Analyses of the Waquoit Bay System - A major component of the MEP nutrient analysis is the evaluation of hydrodynamics within the estuarine system. Although previous hydrodynamic modeling efforts have been performed (e.g. Aubrey et al., 1993 and Valiela et al., 1998), information regarding these analyses are limited. A one-dimensional hydrodynamic model of Waquoit Bay was developed by Aubrey et al. (1993) to study the hydrodynamic effects of both the two and three inlet morphology. Bathymetry data were collected in the main basin of Waquoit Bay, Seapit River, Childs River, and the lower portion of the Quashnet River. Unfortunately, the digital data were not available and the datum described on the depth contour map could not be verified; therefore, the bathymetric information could not be directly incorporated into the present study. If tide gauge measurements were made to parameterize the model, results were not included in Aubrey et al., 1993. In Valiela et al. (1998), results of a circulation model are presented; however, there is no indication whether any physical measurements were performed to parameterize, calibrate, or validate the modeling effort. Again, this effort focused on changes to estuarine flushing with regard to formation of the third inlet by Hurricane Bob in 1991. Similar to Aubrey, et al. (1993), Valiela et al. (1998) conclude that the influence of the third inlet on tidal flushing was relatively minor. The MEP

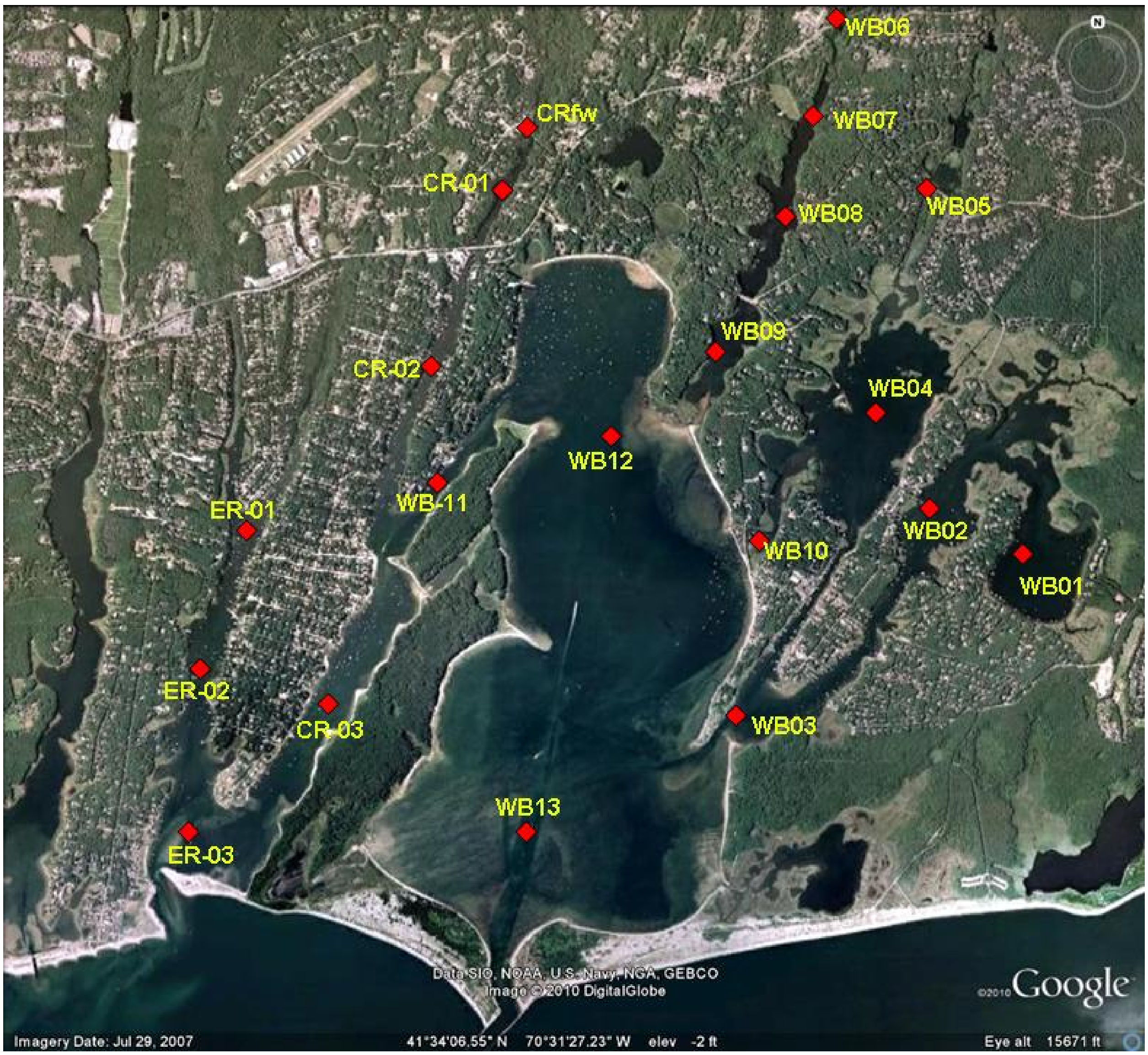


Figure II-1. Water Quality Monitoring Stations in the Waquoit Bay Embayment System, inclusive of Eel Pond and the Childs River (west of main Bay) as well as the Quashnet River, Hamblin Pond and Jehu Pond (east of main Bay).

analysis presented in this report provides a comprehensive analysis of circulation for the entire Waquoit Bay System and an analysis of water quality within the component sub-embayments to the Waquoit Bay Embayment System (Waquoit Bay, Eel Pond, Childs River, Quashnet River, Hamblin Pond and Jehu Pond); therefore, results from the earlier generation 1994 analysis have been superseded.

For the MEP modeling analysis, the data from the previous studies were evaluated relative to the needs of this project. Bathymetric data associated with Aubrey, et al. (1993) was cursory and was not collected relative to a known tidal datum (e.g. NGVD29), as it was collected for a different purpose than system-wide hydrodynamic modeling. Relative to other studies, the Town of Mashpee through their designee contacted the Boston University Marine Program (BUMP) and the Waquoit Bay National Estuarine Research Reserve (WBNERR). Unfortunately, no data associated with physical processes (e.g. tide, current, or bathymetry information) was available for MEP use. As a result, it was necessary to collect new system-wide bathymetry and tide data to support the MEP analysis.

Tidal Flow Investigations for the Childs River - Over the past two years, current data in the Waquoit Bay and Childs River system was collected by Dr. Vitalii Shermet from the University of Rhode Island. Current data collection in Waquoit Bay was initiated in March 2008 and in the Childs River in July 2009. Starting from October 2009, the currents in Childs River (at one site) were measured on a quasi-permanent basis with sampling interval about 1-6 minutes. These data records were generally about 2 weeks to 3 months long with some gaps between each data collection period. In the spring of 2010 Dr. Shermet expanded this current data collection effort at the one location in order to capture current velocities at several depths in the water column to measure the baroclinic flow. This was followed by an experiment conducted in April-May 2011 in which measurements were made to quantify and characterize the propagation of seiches (30min oscillations) within the Childs River. For this 1 month experiment, current measurements were made at 15 locations and tidal elevations were measured at approximately 20 sites. This allowed for the calculation of tidal signal propagation in the Childs River portion of the Waquoit Bay system. In addition to physical measurements, estimates of bio-fouling rates were by made by noting and photographing the instrument housings on recovery. Based on the observations made, the Childs River appears to have elevated levels of bio-fouling especially in the upper reaches. As much of the data were recently collected by Dr. Shermet, it has yet to be fully analyzed and interpreted. Dr. Shermet anticipates having the data synthesized by the end of summer or fall 2011.

To date the work that Dr. Shermet has undertaken in Waquoit Bay has been funded by the Office of Naval Research (ONR). In addition, starting in July, 2011, Dr. Shermet planned to install several flow meters in Childs and Moonakis/Quashnet River in order to better quantify the fresh water flux into Waquoit Bay. That work was sponsored by a small contribution from the Citizens for Protection of Waquoit Bay Organization and it is not known if it has been completed.

Water Quality Monitoring of the Over-all Waquoit Bay System – As part of its mission of long-term monitoring, WBNERR has conducted both a volunteer monitoring program (BayWatcher) and formal monitoring program (System Wide Monitoring Program or SWMP). The WBNERR BayWatcher Program conducts a variety of water quality assays (Secchi Depth, salinity, temperature, dissolved oxygen, and chlorophyll a). Nutrients are also assayed, but only the inorganic forms (ammonium, nitrate, nitrite, ortho-phosphate, silicate). The more formal program (SWMP) is part of the NERR System and employs moored instrumentation to measure dissolved oxygen, salinity, temperature, pH, depth, and turbidity at four mooring sites (upper Waquoit Bay, Childs River, lower Eel Pond, Sage Lot Pond). Organic nitrogen (particulate or dissolved) is not assayed in either monitoring program. Both programs are conducted under the supervision of the WBNERR Staff and the SWMP program is fully vetted through the NERR System. Therefore, the dissolved oxygen and chlorophyll a data collected by both WBNERR Programs has been included in this MEP analysis.

Given the extent of the nitrogen related studies of the Waquoit Bay System, it is unfortunate that there were no water column total nitrogen data available for the previous MEP analysis completed for the Quashnet River, Hamblin Pond and Jehu Pond sub-embayments to the Waquoit Bay System. The absence of data was based upon MEP reviews of existing studies and reports and discussions with WBNERR Staff (September 25, 2003 meeting), as well as discussions between the Town of Mashpee and their wastewater engineering consultant and Boston University Marine Program researchers (Dr. I. Valiela et al.). Estuarine water column and surface freshwater nitrogen measurements included only assays of inorganic nitrogen species (ammonium, nitrate, nitrite) with groundwater assays sometimes including dissolved organic nitrogen. Total nitrogen is required for validation of the MEP Linked Watershed-Embayment Model and other high order estuarine nitrogen models, as nitrogen is rapidly transformed from one species to another. In estuarine systems, like Waquoit Bay, inorganic nitrogen entering from the watershed is rapidly transformed to organic forms. The result is that it is not possible to balance the nitrogen budget for these systems without a full accounting of the nitrogen pool, especially since the inorganic forms account for only a minor fraction of the nitrogen pool in these estuarine waters (generally <5%).

As a result of the absence of water column total nitrogen data, the Town of Mashpee with the Coastal Systems Program (CSP) at SMAST-UMD conducted system-wide surveys of nitrogen levels throughout the Waquoit Bay Embayment System and associated waters. The initial water quality surveys were undertaken to support the MEP analysis of the Quashnet River, Hamblin Pond and Jehu Pond. The Program was extended to capture water quality throughout the Waquoit Bay System, in order to support the current MEP analysis to include the Waquoit Bay, Eel Pond and Child River sub-embayments. The specific goal of the water quality surveys was to capture the nitrogen gradients within these estuaries to support the MEP Linked Watershed-Embayment Modeling effort. Water quality monitoring is conducted during the summer when eutrophication impacts are generally the greatest in Cape Cod embayments. The initial findings were that nitrogen levels throughout the tidal reaches of the Waquoit Bay System are significantly elevated over the flood waters of Nantucket Sound, that nitrogen is the key management nutrient throughout the tidal reaches of this estuary (consistent with previous studies), that the sub-embayments receiving the major surface water inflows (Childs and Quashnet Rivers) are eutrophic and showing significant impairment from nitrogen enrichment, and that inorganic nitrogen generally accounts for <5% of the total nitrogen pool within the Bay waters. In addition, the sub-systems showed gradients in both nitrogen and salinity typical of impaired estuaries throughout the region.

The water quality sampling that was conducted as a joint effort between private citizens, the Mashpee Shellfish Department, Mashpee Harbor Master, Mashpee Waterways Commission, Mashpee Watershed Nutrient Management Committee, and SMAST. This program has recently been formalized as the collaborative Mashpee Water Quality Monitoring Program, coordinated by the Mashpee Waterways Commission as a partnership between the Mashpee Wampanoag Tribe, Town of Mashpee and Coastal Systems Program-SMAST-UMD. The Program has volunteers from both Mashpee and Falmouth, with additional field support from WBNERR.

After extensive review and evaluation of previous and on-going studies conducted in Waquoit Bay, the MEP Technical Team has attempted to incorporate all appropriate data from all sources. The objective of the in-depth review of previous studies was to enhance the determination of nitrogen thresholds for the component sub-embayments to the Waquoit Bay System and to reduce costs to the Towns of Mashpee and Falmouth.

On-going Pertinent Research Programs at the Waquoit Bay National Estuarine Research Reserve - Sedimentalogical Processes and the Evolution of Waquoit Bay is a collaborative project between scientists from Woods Hole Oceanographic and WBNERR. This is a long-term, multi-phase project (really more of a research program wish list) whose primary purpose is to better understand the geological evolution of Waquoit Bay. Central to that goal is investigating the processes: oceanic, estuarine, terrestrial, climatic and biological that have operated in the past and currently operate that affect the bay's sediment system. Despite a wealth of current ecological and hydrological data on Waquoit Bay, designated as one NOAA's National Estuarine Research Reserves in 1988, little is known about its evolution or that of many similar embayments in the region -- particularly, how fast they respond to changing environmental conditions. Current work and research plans includes: 1) monitoring shoreline change and morphology along the entire 3-miles of south-facing barrier beach fronting Waquoit Bay, 2) sediment core analysis including down-core radiocarbon-dating, radiometric dating and sediment-size, 3) wave and current analysis, and 4) sub-surface geophysical imaging. Partnerships or collaborations are actively welcomed to broaden and deepen these studies (WBNERR Project Brief).

Excess Nitrogen Entering a Coastal System from Vehicle Exhaust is an ongoing project being undertaken by researchers from Cornell University, the Marine Biological Laboratory in Woods Hole and the Woods Hole Research Center. This investigation is focusing on atmospheric nitrogen deposition onto land, so-called 'dry deposition,' which is another potentially large source of nitrogen input to the coast, one that is difficult to measure. In a continuation of Sea Grant-funded work, researchers Robert Howarth and Roxanne Marino (both of Cornell University) and Eric Davidson (Woods Hole Research Center) think that the deposition of nitrogen from vehicle exhaust in urban or seasonally populous areas has been underestimated in past studies. Previous work by these researchers showed high rates of nitrogen deposition near heavily-traveled roadways. This project continues their study of this problem. Howarth, Marino, and Davidson will quantify nitrogen deposition along Cape Cod roadways using three measurements: bulk nitrogen deposition (the nitrogen found in sample buckets, comprising the N in rainfall plus the N from aerial deposition into the buckets during the collection time); "throughfall" (material falling through the tree canopy, which includes the N in rainfall plus nitrogen compounds deposited on the leaves from dry sources and washed off in the rain); and estimates of the dry deposition based on calculations of N gas concentration in the air (WHOI-Sea Grant Project Brief).

Regulatory Assessments of Waquoit Bay and Eel Pond Resources - The Waquoit Bay / Eel Pond Estuary and the tributary sub-embayments of Hamblin and Jehu Ponds contain a variety of natural resources of value to the citizens of Falmouth as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP gathers the available information on these resources as part of its assessment, and presents them here (Figures II-2 through II-6) for reference by those providing stewardship for this estuary. For the Waquoit Bay Estuary these include:

- ♦ Mouth of River designation - MassDEP (Figure II-2a,b,c,d,e,f)
- ♦ Designated Shellfish Growing Area – MassDMF (Figure II-3)

- Shellfish Suitability Areas - MassDMF (Figure II-4a,b)
- Anadromous Fish Runs - MassDMF (Figure II-5)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-6a,b)

Figure II-2a. Regulatory designation of the mouth of the Childs River under the Massachusetts River Act, as determined by MassDEP. Upland adjacent the shore or "river front" inland of the mouth of the river has restrictions specific to the Act.

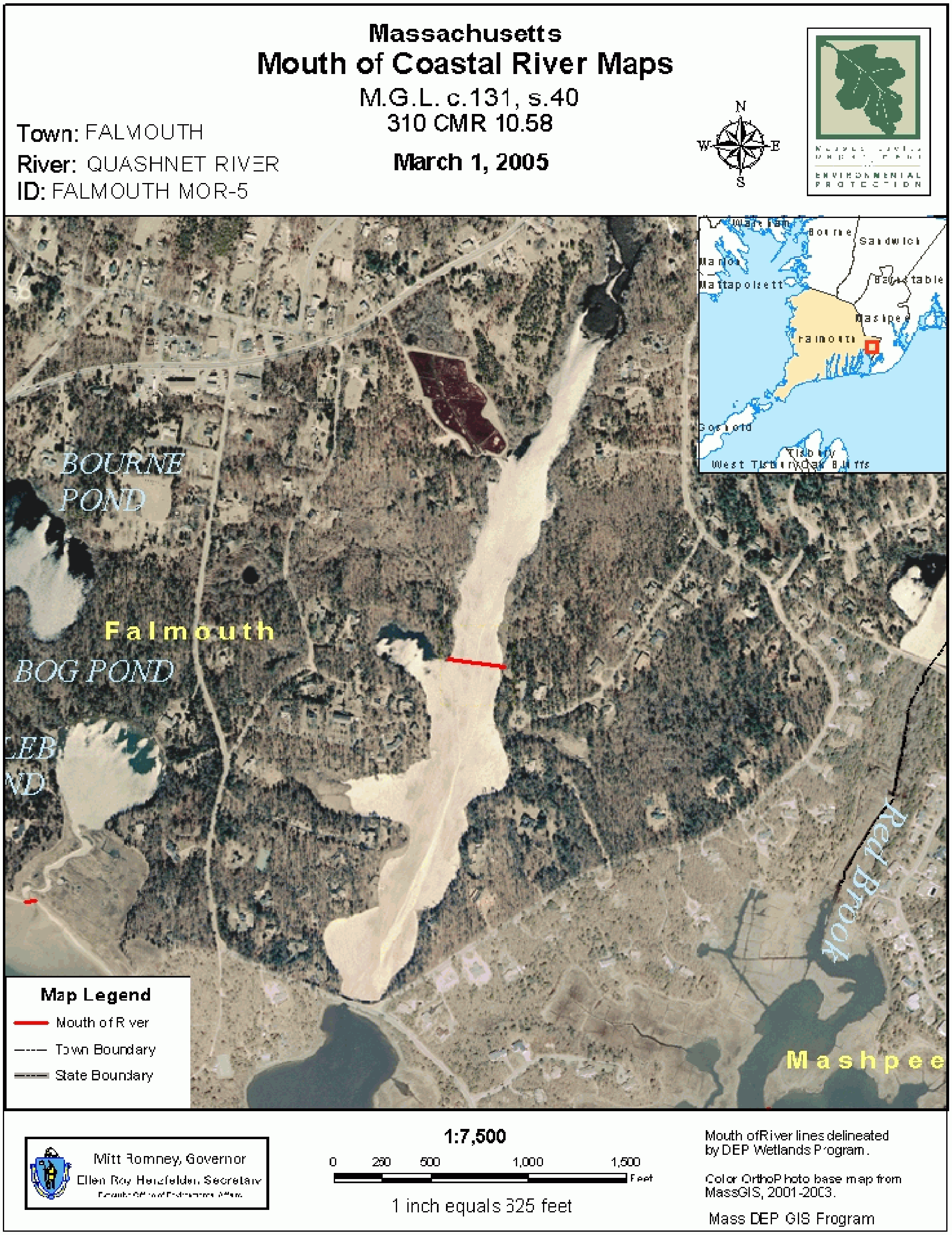


Figure II-2b. Regulatory designation of the mouth of the Quashnet River discharging into the Waquoit Bay Estuary under the Massachusetts River Act, as determined by MassDEP. Upland adjacent the shore or "river front" inland of the mouth of the river has restrictions specific to the Act.

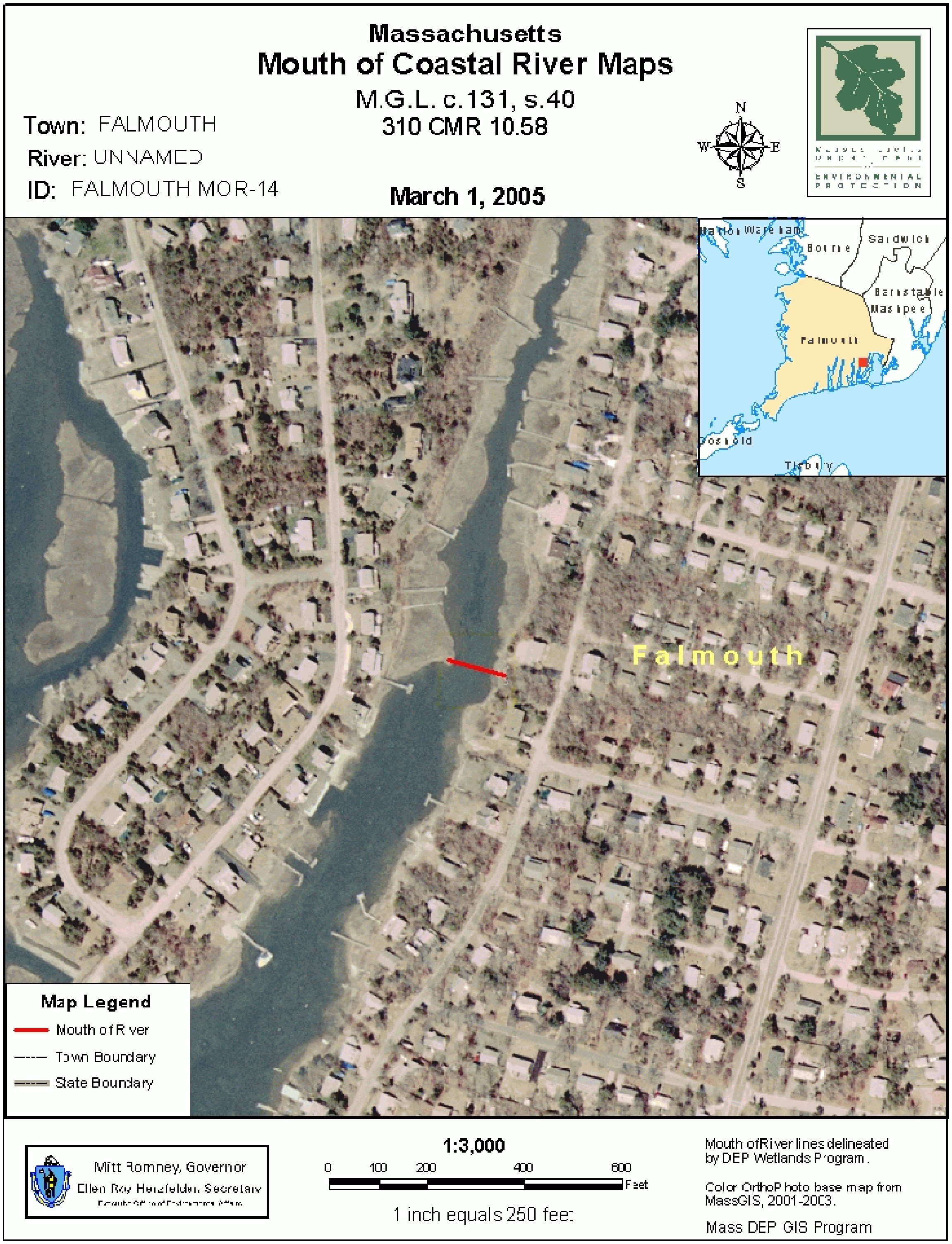


Figure II-2c. Regulatory designation under the Massachusetts River Act (MassDEP) of the east fork at the head of Eel Pond which is hydrodynamically connected to the Waquoit Bay Estuary via the Seapit River. Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

Figure II-2d. Regulatory designation under the Massachusetts River Act of the mouth of the tidal channel to Caleb Pond at the head of the Waquoit Bay Estuary, as determined by MassDEP. Upland adjacent the shore or "river front" inland of the mouth of the “river” has restrictions specific to the Act.

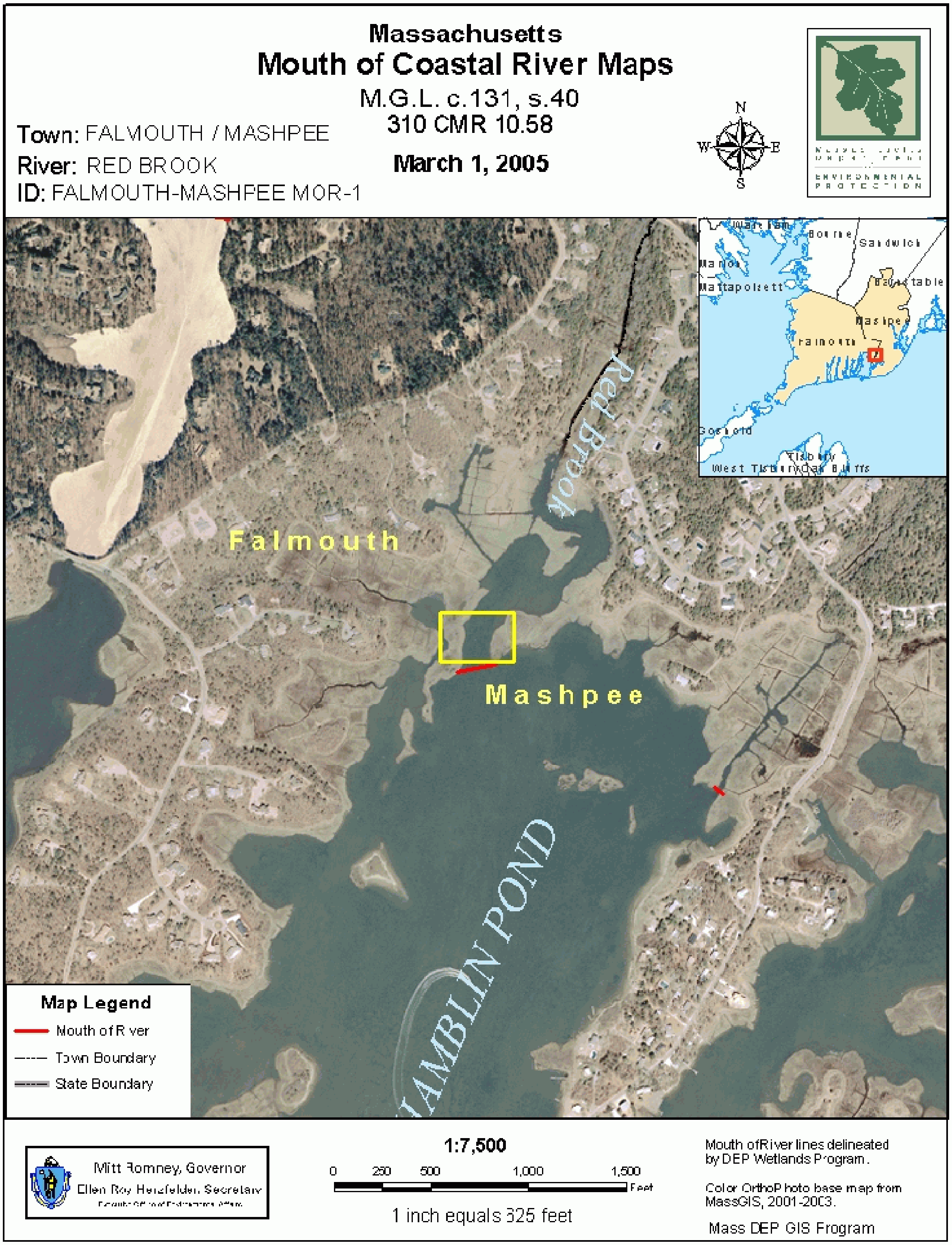


Figure II-2e. Regulatory designation under the Massachusetts River Act of the mouth of Red Brook and an un-named tidal creek at the head of the Hamblin Pond sub-embayment, tributary to the Waquoit Bay Estuary, as determined by MassDEP. Upland adjacent the shore or "river front" inland of the mouth of the "river" has restrictions specific to the Act.

Figure II-2f. Regulatory designation under the Massachusetts River Act (MassDEP) of the mouth of Abigail Brook, a tidal creek at the head of the Jehu Pond sub-embayment, tributary to the Waquoit Bay Estuary, as determined by MassDEP. Upland adjacent the shore or "river front" inland of the mouth of the “river” has restrictions specific to the Act.

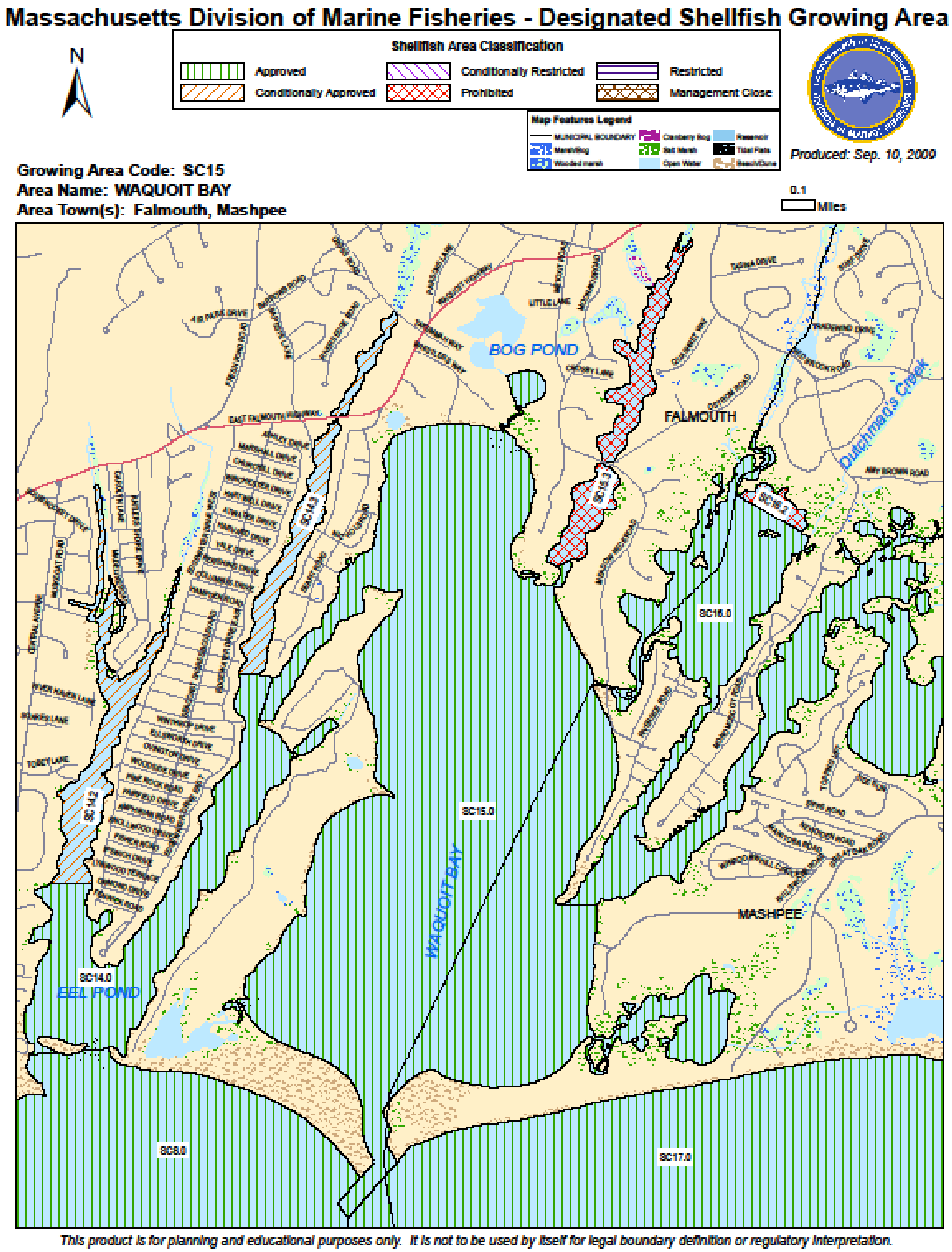


Figure II-3. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

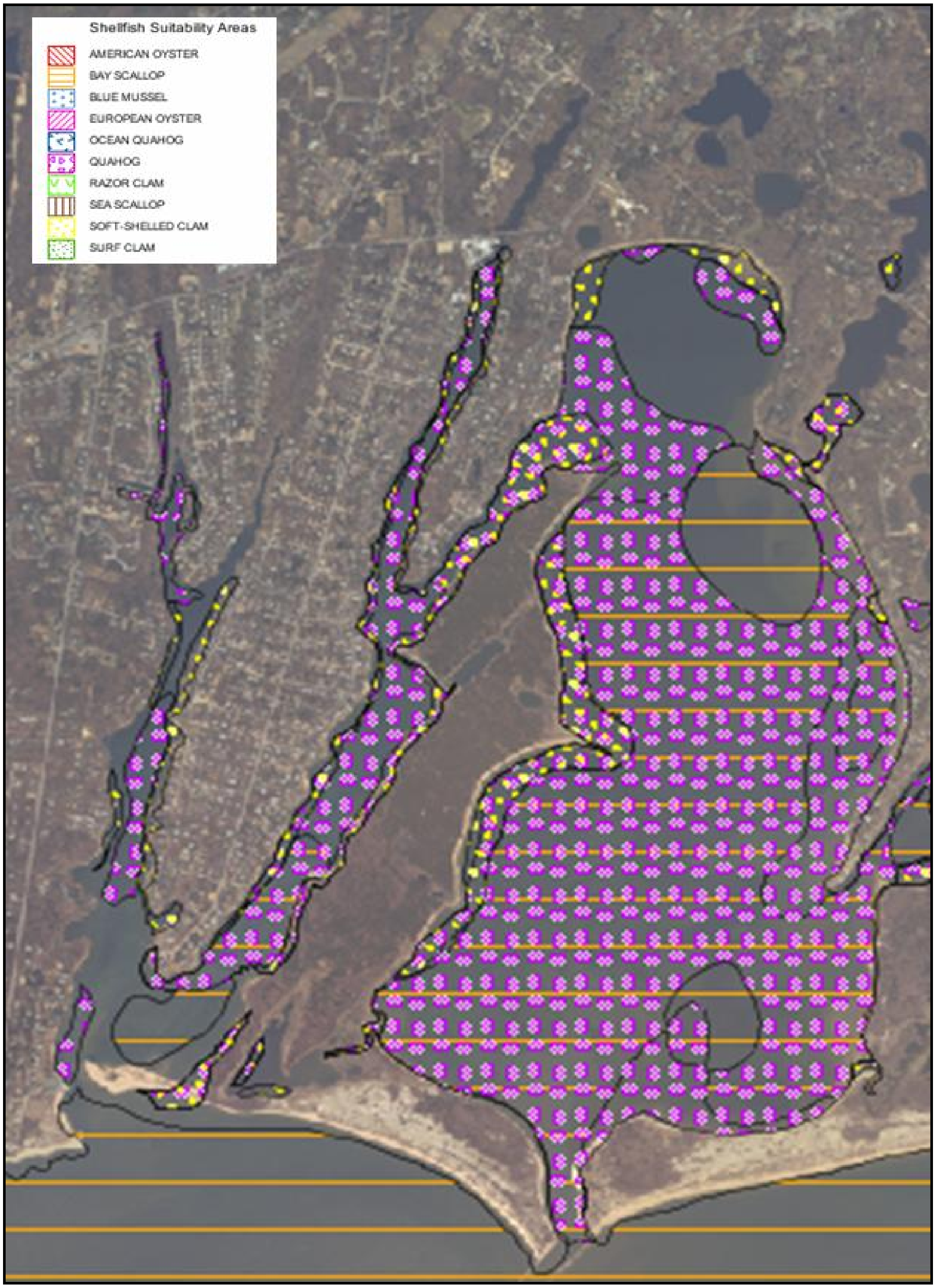


Figure II-4a. Location of shellfish suitability areas within the Eel Pond / Waquoit Bay Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence" and much of the shellfish habitat is presently impaired by nitrogen enrichment effects. The main Bay historic bay scallop habitat is degraded by loss of eelgrass coverage and accumulations of macroalgae.

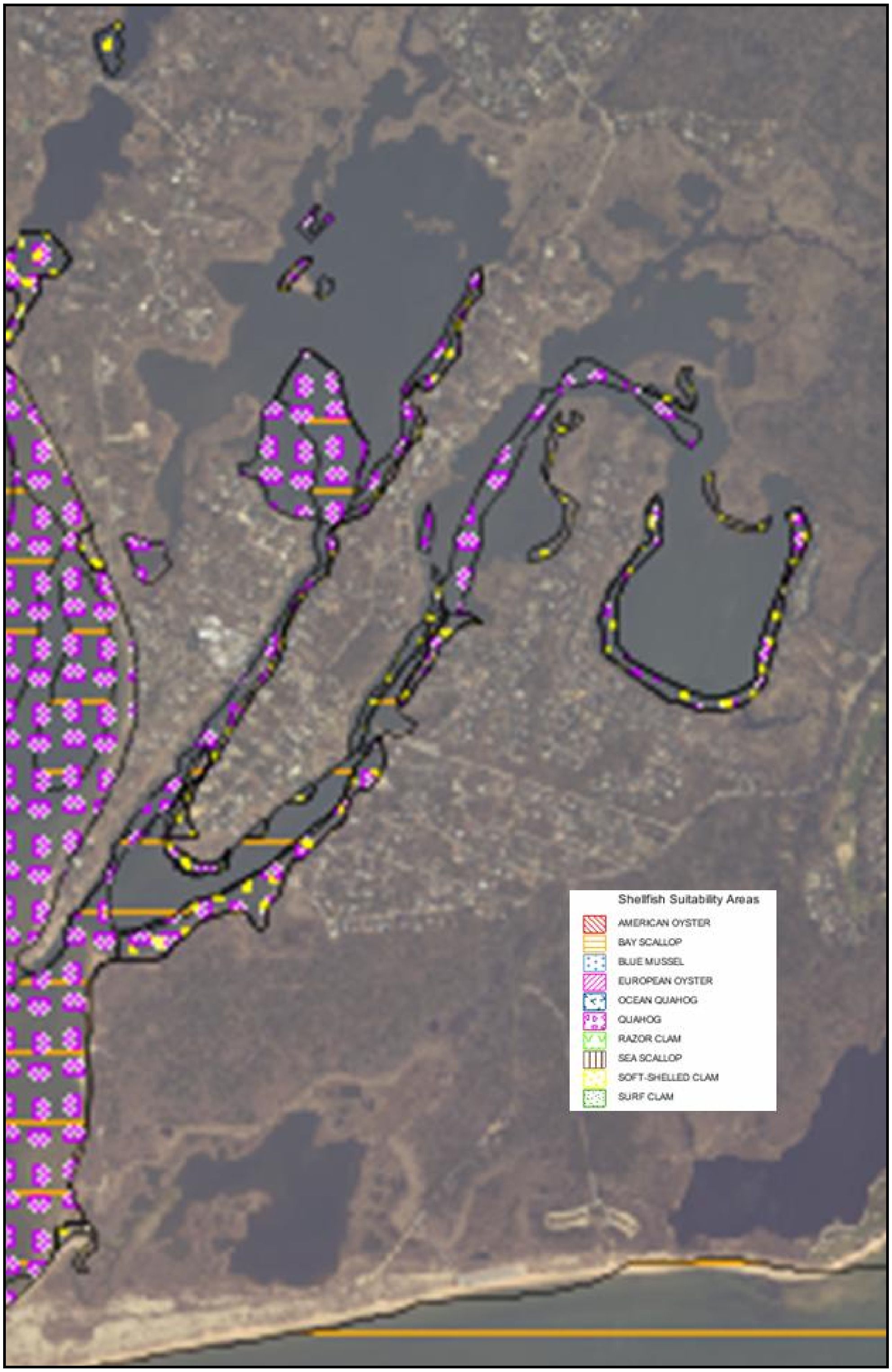


Figure II-4b. Location of shellfish suitability areas within the Hamblin Pond and Jehu Pond sub-embayments to the Waquoit Bay Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

Figure II-5. Anadromous fish runs within the Childs River and Quashnet River tributaries to the Waquoit Bay Estuary as determined by Mass Division of Marine Fisheries. The red diamonds show areas where fish were observed.

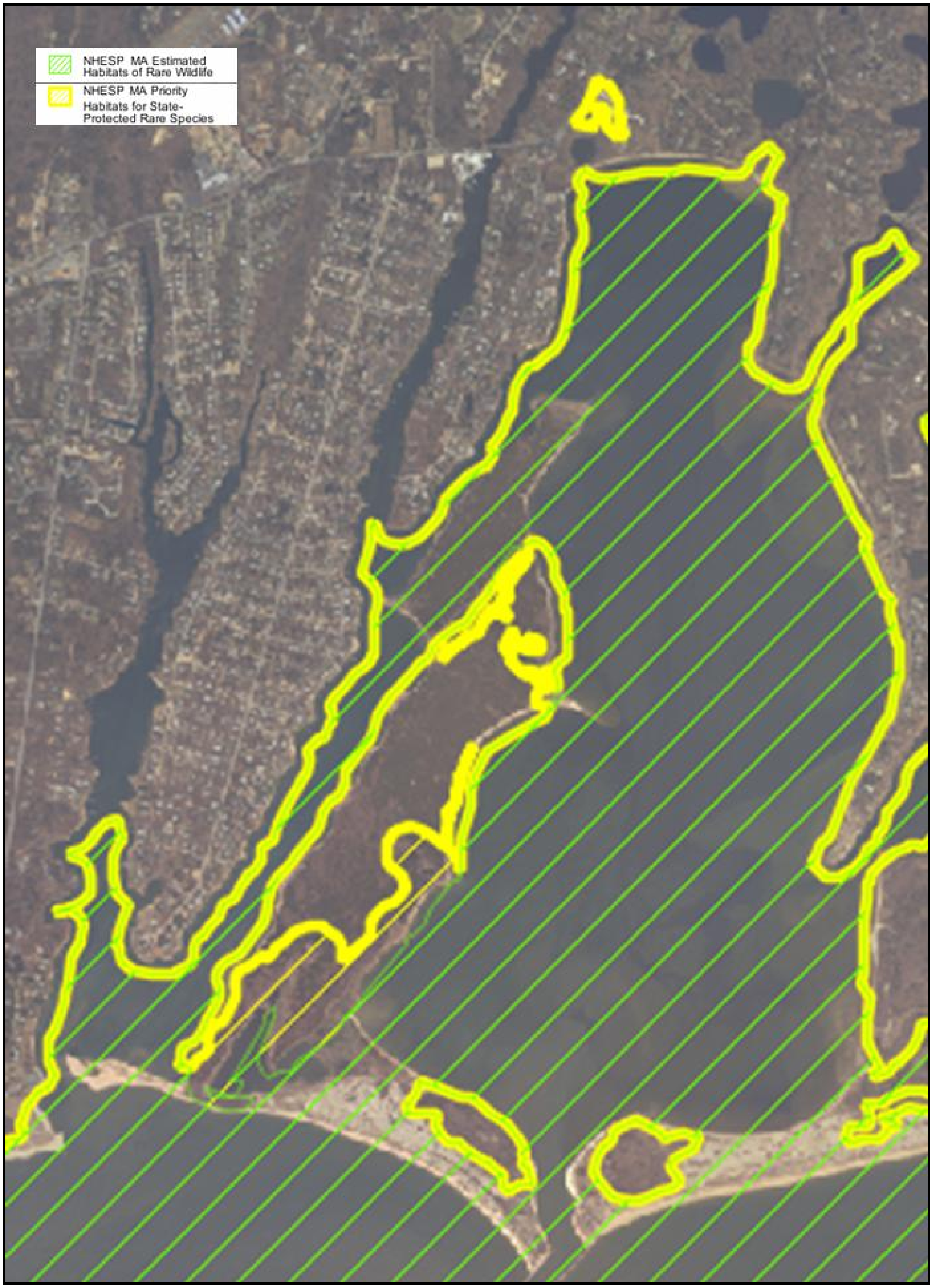


Figure II-6a. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Eel Pond and Waquoit Bay Estuary as determined by - NHESP.

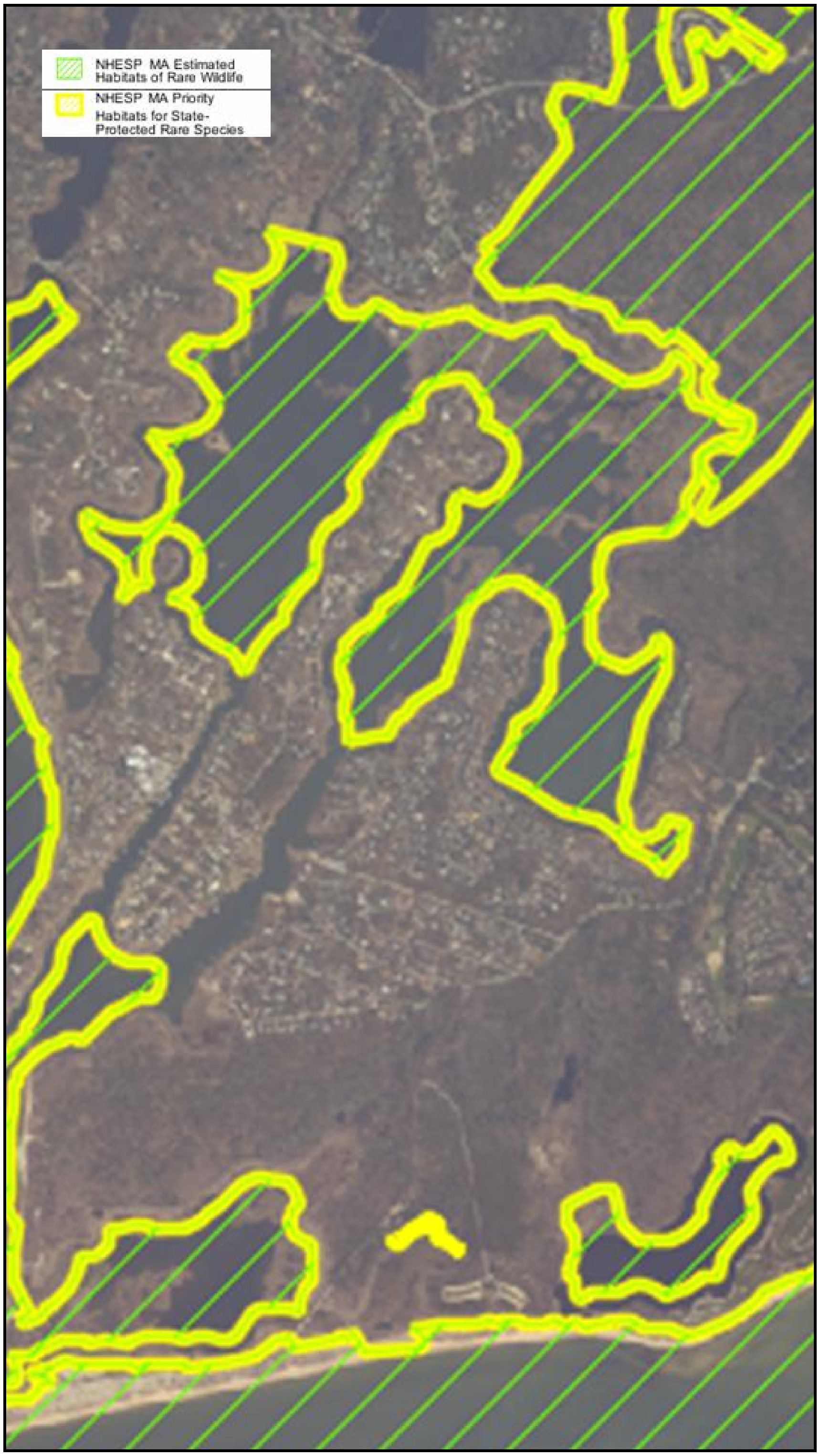


Figure II-6b. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Hamblin Pond and Jehu Pond sub-embayments, tributary to the Waquoit Bay Estuary as determined by - NHESP.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

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

In the present investigation, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the Waquoit Bay Embayment System under evaluation by the Project Team. The Waquoit Bay Embayment System is a shallow embayment that presently supports three inlets (two main and one recent minor) to Vineyard Sound. Watershed modeling was undertaken to sub-divide the overall watershed to the Waquoit Bay Embayment System into the sub-watersheds that contribute to each of the component sub-embayments of the estuary 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 time-of-travel distributions within each sub-watershed are used as a procedural check to gauge the potential mass of nitrogen from “new” development, which has not yet reached the receiving estuarine waters at the time of the MEP analysis. The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in the Sagamore flow cells on Cape Cod; the Waquoit Bay Embayment System watershed is located within the Sagamore groundwater lens. Model assumptions for calibration of the Waquoit Bay Estuary included surface water discharges measured as part of the MEP stream flow program (2006 to 2007).

The relatively transmissive sand and gravel deposits that constitute 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 to estuarine waters, as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Waquoit Bay Embayment System and its various sub-watersheds, such as Ashumet and Johns Ponds and the Quashnet and Childs Rivers, were delineated using the regional model of the Sagamore Lens flow cell (Walter and Whealan, 2005). The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, *et al.*, 2000) was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4 (Pollock, 2000), which uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies. This approach was used to determine the contributing area to the Waquoit Bay Estuary and its component sub-watersheds and also to determine portions of recharged water that may flow through fresh water ponds and streams prior to discharging into estuarine waters.

The Sagamore Flow Model grid consists of 246 rows, 365 columns and 20 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top 17 layers of the model extend to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft. The top of layer 8 resides at NGVD 29 with layers 1-7 stacked above and layers 8-20 below. Layer 18 has a thickness of 40 feet and extends to 140 feet below NGVD 29, while layer 19 extends to 240 feet below NGVD 29. The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics (up to 519 feet below NGVD 29 in the Sagamore Lens). In the watershed to the Waquoit Bay Embayment System, bedrock gradually descends from a depth of approximately 200 feet below NGVD 29 in the northern portions of the watershed to more than 400 feet below NGVD near the estuary inlets (Walter and Whealan, 2005). In the groundwater flow model, this means that the lowest model layer is inactive in the northern portion of the watershed and active in the southern part of the watershed. 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.

The glacial sediments that constitute the aquifer of the Sagamore Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The Waquoit Bay System watershed is located in the Mashpee Outwash Plains Deposits, in which the sediments generally show a fining downward with sand and gravel deposits deposited in glaciofluvial (river) and near-shore glaciolacustrine (lake) environments underlain by fine sand, silt and clay deposited in deeper, lower-energy glaciolacustrine environments. Glacial collapse structures caused by melting of remnant ice blocks form the kettle hole depressions that are now freshwater ponds. Most groundwater flow in the aquifer occurs in shallower portions of the aquifer, which are dominated by coarser-grained sand and gravel deposits (Walter and Whealan, 2005). Modeling and field measurements of contaminant transport at the Massachusetts Military Reservation have shown that Mashpee Outwash Plains Deposits are permeable (*e.g.*, Masterson, *et al.*, 1996) with relatively high hydraulic conductivity. Direct rainwater run-off in these materials is typically rather low as is seen in most of the Cape. Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from USGS, local Town records and data from previous investigations. Final aquifer parameters in the groundwater models were determined through calibration to observed water levels and stream flows. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Towns and stream flow data collected in 1989-1990 as well as 2003.

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

III.3 WAQUOIT BAY EMBAYMENT SYSTEM CONTRIBUTORY AREAS

The refined watershed and sub-watershed boundaries for the Waquoit Bay Embayment System, including Bournes, Moody, Weeks, Snake, Ashumet and Johns Ponds and the Quashnet and Childs Rivers, along with the other component sub-embayments (Eel Pond, Waquoit Bay, Hamblin Pond, Jehu Pond, and Sage Lot/Flat Pond) were determined by the United States Geological Survey (Figure III-1). Model outputs of the watershed boundaries were "smoothed" to (a) correct for the grid spacing, (b) to enhance the accuracy of the characterization of the pond and coastal shorelines, (c) include water table data in the lower regions of the watersheds near the coast (as available), (d) to more closely match the sub-embayment basins of the tidal hydrodynamic model and (e) to address streamflow measurements collected as part of the MEP. The smoothing refinement was a collaborative effort between the USGS and the rest of the MEP Technical Team. The MEP sub-watershed delineation also includes 10-yr time-of-travel boundaries as a procedural check on the balance of watershed to estuary nitrogen loading. Overall, 48 sub-watershed areas were delineated within the contributing area to the Waquoit Bay Embayment System.

Table III-1 provides the daily freshwater discharge volumes for the sub-watersheds as calculated from the groundwater model; these volumes were used in the salinity calibration of the tidal hydrodynamic model and to determine hydrologic turnover in the lakes/ponds, as well as for comparison to the directly measured surface water discharges. The overall estimated freshwater flow into the Waquoit Bay Embayment System from the MEP delineated watershed is 98,982 m3/d. This flow includes corrections for outflow from Snake and Ashumet Ponds, which straddle the boundary of the Waquoit Bay Embayment System watershed with the Popponesset Bay MEP watershed (Howes, *et al*., 2004) and Green and Bournes Ponds MEP watersheds (Howes, *et al*., 2005a), respectively. The flow is also corrected for recharge removed by the MMR J Well, which supplies drinking water to the Massachusetts Military Reservation and removes the pumped recharge and nitrogen within its contributing area from the Waquoit Bay/Eel Pond MEP watershed. This well also captures and removes a portion of the Weeks Pond recharge.

The MEP watershed delineation is the second watershed delineation completed in recent years for the Waquoit Bay Embayment System. Figure III-2 compares the delineation completed under the current effort with the delineation completed by the Cape Cod Commission as part of the Coastal Embayment Project (Eichner, *et al*., 1998). The CCC delineation was largely based on data collected for and presented in *Watershed Delineation and Ground Water Discharge to a Coastal Embayment* (Cambareri and Eichner, 1998), as well as on regional water table measurements collected from available well data over a number of years and normalized to average conditions. The Commission's delineation was incorporated into the Commission's regulations through the three versions of the Regional Policy Plan (CCC, 1996, 2001, and 2009). The current delineation also incorporates the MEP delineation completed for East Waquoit in Howes and others (2005b).

The MEP watershed area for the Waquoit Bay Embayment System as a whole is 6% larger than 1998 CCC delineation (15,021 acres vs. 14,106 acres, respectively). These areas include the estuary surface areas and do not include any of the corrections for outflow in either delineation. A large portion of the difference is the inclusion of Flat Pond contributing area within the MEP watershed area. The MEP watershed delineation also includes much more refined interior sub-watersheds to various components of the Waquoit Bay Embayment System, such as selected ponds and streams that were not included in the CCC delineation. The inner sub-watershed delineations show the connections between adjacent watersheds and the complexities of flow paths. These refinements are another benefit of the updated regional groundwater model (Walter and Whealan, 2005).

The evolution of the watershed delineations for the Waquoit Bay Embayment System has allowed increasing accuracy as each new version adds new hydrologic data to that previously collected; the model allows all this data to be organized and to be brought into congruence with adjacent watersheds. The evaluation of older data and incorporation of new data during the development of the model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model and strengthens the analysis for the use of this model as a tool for evaluating nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon the land-uses that are included/excluded within the contributing areas. Small errors in watershed area can result in large errors in loading if a large source is counted in or out. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the down gradient estuary. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the aquatic systems and ultimately to the estuarine waters of the Waquoit Bay Embayment System as described in Section IV.1 and utilized in Section VI.

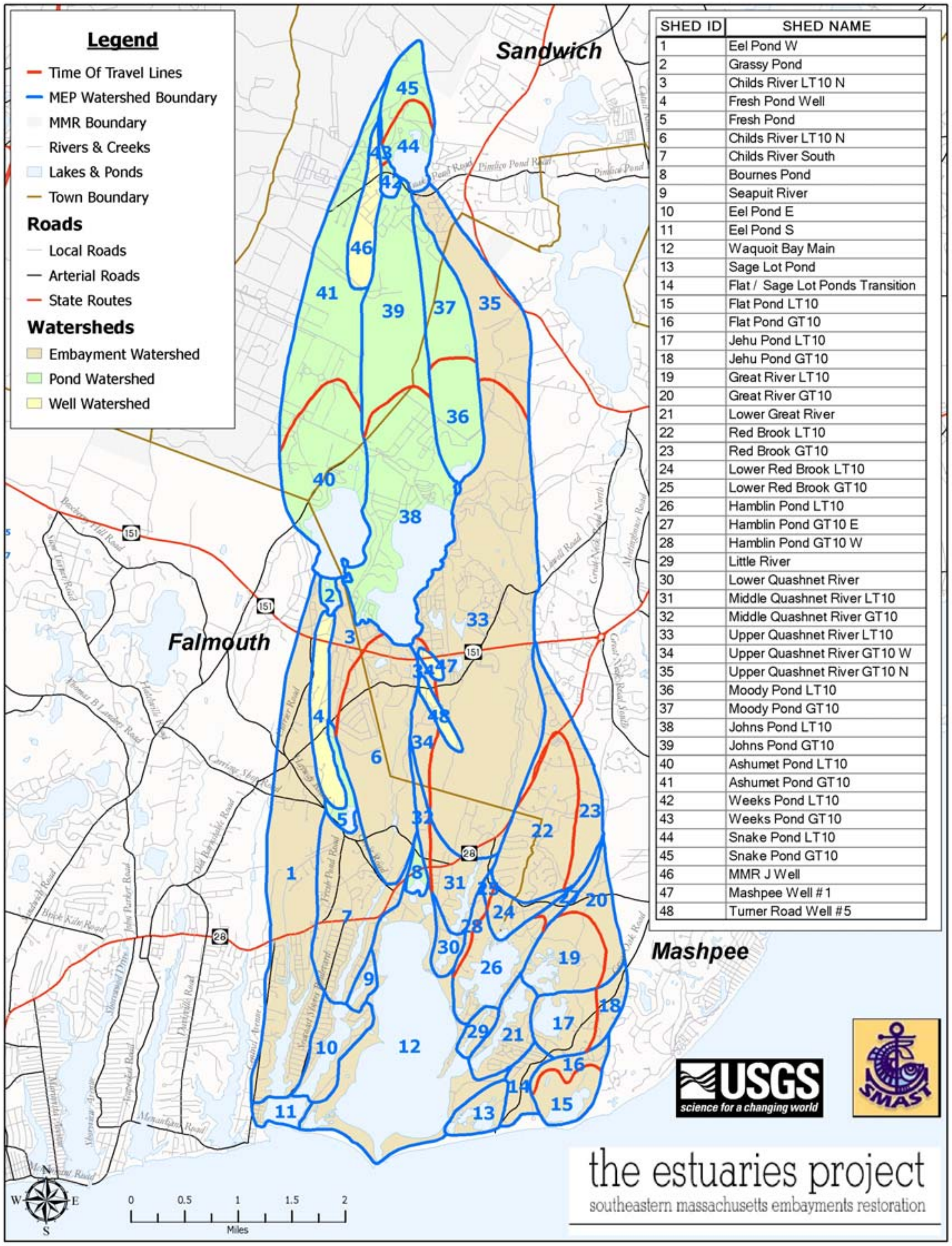


Figure III-1. Watershed delineation for the Waquoit Bay Embayment System. Sub-watershed delineations are based on USGS groundwater model output refined for pond and estuary shorelines and MEP stream gauge measurements. Ten-year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names ("LT10": <10 yr; "GT10": >10 yr). Recharge from the Snake Pond watershed is shared with the Popponesset Bay MEP watershed (Howes, *et al*., 2004), while recharge from the Ashumet Pond watershed is shared with Green and Bournes Ponds MEP watersheds (Howes, *et al*., 2005a).

Table III-1. Daily groundwater discharge from each of the sub-watersheds comprising the contributing area to the Waquoit Bay Embayment System, as determined from the regional USGS groundwater model. Ten-year time-of-travel delineations are designated,"LT10" for <10 year travel time and "GT10" for >10 year travel time.

Watershed	#	Watershed Area (acres)	% contributing to Estuaries	Discharge	
				m^3/day	ft^3/day
Eel Pond W	1	1,104	100%	8,472	299,186
Grassy Pond	2	32	100%	245	8,652
Childs R N GT10	3	172	100%	1,323	46,721
Fresh Pond Well	4	199	100%	1,525	53,855
Fresh Pond	5	71	100%	544	19,211
Childs R N LT10	6	800	100%	6,137	216,726
Childs R South	7	530	100%	4,069	143,695
Bournes Pond	8	45	100%	345	12,184
Seapuit River	9	34	100%	263	9,288
Eel Pond E	10	148	100%	1,132	39,976
Eel Pond S	11	27	100%	204	7,204
Waquoit Bay Main	12	388	100%	2,981	105,273
Sage Lot Pond	13	78	100%	601	21,224
Flat/Sage Lot Ponds Transition	14	109	100%	838	29,594
Flat Pond LT10	15	161	100%	1,238	43,720
Flat Pond GT10	16	75	100%	574	20,271
Jehu Pond LT10	17	154	100%	1,182	41,742
Jehu Pond GT10	18	88	100%	672	23,731
Great River LT10	19	244	100%	1,874	66,180
Great River GT10	20	164	100%	1,259	44,461
Lower Great River	21	144	100%	1,106	39,058
Red Brook LT10	22	505	100%	3,874	136,809
Red Brook GT10	23	291	100%	2,235	78,928
Lower Red Brook LT10	24	106	100%	812	28,676
Lower Red Brook GT10	25	15	100%	112	3,955
Hamblin Pond LT10	26	174	100%	1,339	47,286
Hamblin Pond GT10E	27	48	100%	368	12,996
Hamblin Pond GT10W	28	38	100%	294	10,383
Little River	29	48	100%	370	13,066

Table III-1 (continued). Daily groundwater discharge from each of the sub-watersheds in the watershed to the Waquoit Bay Embayment System estuary, as determined from the regional USGS groundwater model.

Lower Quashnet River	30	55	100%	422	14,903
Middle Quashnet River LT10	31	207	100%	1,590	56,150
Middle Quashnet River GT10	32	63	100%	486	17,163
Upper Quashnet River LT10	33	2,216	100%	17,009	600,667
Upper Quashnet River GT10W	34	125	100%	958	33,831
Upper Quashnet River GT10N	35	498	100%	3,823	135,008
Moody Pond LT10	36	298	100%	2,286	80,729
Moody Pond GT10	37	285	100%	2,187	77,233
Johns Pond LT10	38	1,014	100%	7,783	274,854
Johns Pond GT10	39	632	100%	4,848	171,206
Ashumet Pond LT10	40	718	85%	4,662	165,414
Ashumet Pond GT10	41	716	85%	4,650	164,990
Weeks Pond LT10	42	30	70%	159	5,615
Weeks Pond GT10	43	11	70%	58	2,048
Snake Pond LT10	44	177	54%	734	25,921
Snake Pond GT10	45	145	54%	601	21,224
MMR J Well	46	168	0%	0	-
Mashpee Well No. 1	47	23	100%	180	6,357
Turner Road Well No. 5	48	51	100%	393	13,879
TOTAL WAQUOIT BAY EMBAYMENT SYSTEM				98,982	3,495,522

Notes: 1) discharge volumes are based on 27.25 inches of annual recharge on adjusted watershed areas (total watershed areas are shown); 2) Ashumet Pond is shared with Green and Bournes Pond MEP watersheds (Howes, *et al*., 2005a), Snake Pond is shared with the Popponesset Bay MEP watershed (Howes, *et al*., 2004), percentage of flow from these ponds is determined by length of downgradient watershed boundary, 3) MMR J Well supplies drinking water to the Massachusetts Military Reservation and removes recharge and nitrogen within its contributing area from the Waquoit Bay System MEP watershed, this well also captures a portion of the Weeks Pond recharge, 4) listed flows do not include precipitation on the surface of the estuary, 5) totals may not match due to rounding.

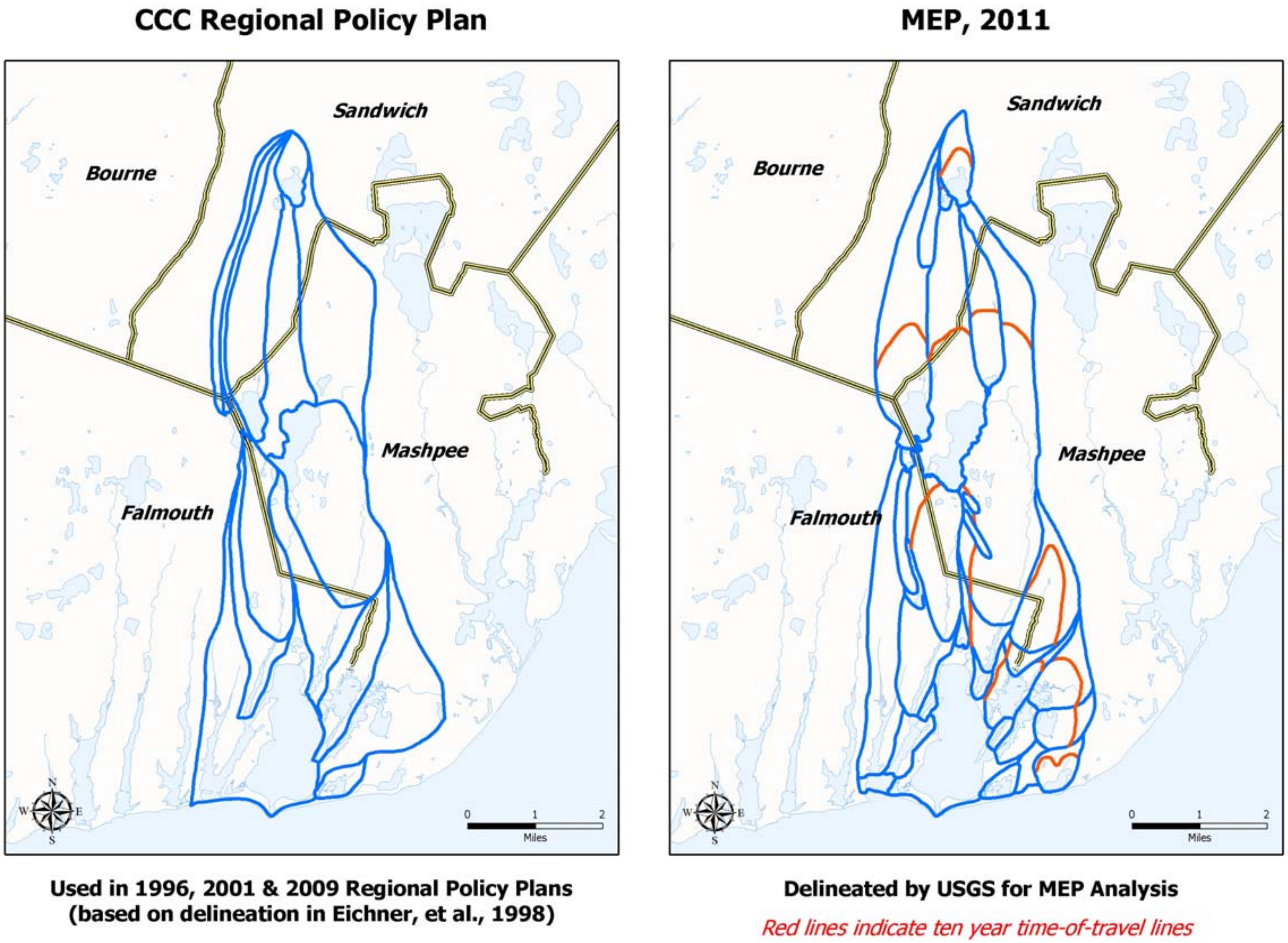


Figure III-2. Comparison of MEP Waquoit Bay Embayment System watershed and sub-watershed delineations used in the current assessment and the earlier Cape Cod Commission watershed delineation (Eichner, *et al*., 1998), used in three Barnstable County Regional Policy Plans (CCC, 1996, 2001, 2009). The MEP watershed area for the Waquoit Bay Estuary as a whole is 6% larger than 1998 CCC delineation, primarily due to inclusion of Flat Pond. A total of 48 sub-watersheds, including time-of-travel delineations were determined from the USGS regional modeling effort.

IV. WATERSHED NITROGEN LOADING TO EMBAYMENT: LAND USE, STREAM INPUTS, SEDIMENT NITROGEN FLUX AND 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 Waquoit Bay Embayment System. Determination of watershed nitrogen inputs to these embayment systems requires the (a) identification and quantification of the nutrient sources and their loading rates to the land or aquifer, (b) confirmation that a groundwater transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes prior to reaching the estuary. This latter natural attenuation process results from biological activity that naturally occurs within these ecosystems. Failure to account for attenuation of nitrogen during transport results in an over-estimate of nitrogen inputs to an estuary and an underestimate of the sensitivity of a system to new inputs (or removals). In addition to the nitrogen transport from land to sea, the amount of direct atmospheric deposition on each embayment surface must be determined as well as the amount of nitrogen recycling within the embayment, specifically nitrogen regeneration from sediments. Sediment nitrogen recycling results primarily from the settling and decay of phytoplankton and macroalgae (and eelgrass when present). During decay, organic nitrogen is transformed to inorganic forms, which may be released to the overlying waters or lost to denitrification within the sediments. Permanent burial of nitrogen in the sediments is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source of nitrogen to embayment waters or in some cases a sink for nitrogen reaching the bottom of an estuary. Failure to include the nitrogen balance of estuarine sediments and the watershed attenuation generally leads to errors in predicting water quality, particularly in the determination of summertime nitrogen load to embayment waters.

In order to determine watershed nitrogen loading inputs to the Waquoit Bay Embayment System, the MEP Technical Team developed nitrogen-loading rates (Section IV.1) to each component of the estuary and its watersheds (Section III). The Waquoit Bay Embayment System watershed was sub-divided to define contributing areas or sub-watersheds to each of the major inland freshwater systems and to each major portion of the estuary. Further sub-divisions were made to identify watershed areas where a nitrogen discharge reaches estuary waters in less than 10 years or greater than 10 years. A total of 48 sub-watersheds were delineated in the overall Waquoit Bay Embayment System watershed, including watersheds to the following freshwater ponds: Snake, Grassy, Fresh, Weeks, Ashumet, Moody, Bournes, and Johns. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and each portion of the estuary (see Section III).

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the estuary. This involves a temporal review of land use changes, the time of groundwater travel provided by the USGS watershed model, and review of data at natural collections points, such as streams and ponds. Evaluation and delineation of ten-year time of travel zones are a regular part of the watershed analysis. Ten-year time of travel sub-watersheds in the Waquoit Bay Embayment System watershed have been delineated for ponds, streams and the estuary itself. Review of less than and greater than 10-yr time of travel watersheds indicates that 75% 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 includes refinements for flow leaving the overall watershed from ponds along its outer boundary. If the loads from precipitation on the estuary surface are added, the percentage that reaches the estuary within 10 years increases to 78%. The overall result of the timing of development relative to groundwater travel times is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuary (after accounting for natural attenuation, see below). Additionally, the distinction between time of travel in the sub-watersheds is not significant for the modeling of existing conditions. Overall and based on the review of all this information, it was determined that the Waquoit Bay Embayment is currently in balance with its watershed load.

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data are used for some portion of the loads, while information developed from other detailed site-specific studies is applied to other portions. The Linked Watershed-Embayment Management Modeling Approach (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon sub-watershed-specific land uses and pre-determined nitrogen loading rates based on regional analyses. For the Waquoit Bay Embayment System, the model used land-use data from the Towns of Mashpee, Falmouth, and Sandwich, transformed into nitrogen loads using both regional nitrogen loading factors and local watershed-specific data (such as parcel by parcel water use and alternative septic system monitoring). Determination of the nitrogen loads required obtaining watershed specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the “potential” or unattenuated nitrogen load to each receiving embayment, since attenuation during transport is included at a later stage.

Natural attenuation of nitrogen during transport from land-to-sea (Section IV.2) within the Waquoit Bay Embayment System watershed was determined based upon a site-specific study of streamflow and assumed and measured attenuation in the up-gradient freshwater ponds. Streamflow was characterized near the Martin Road crossing of the Quashnet River and near the Barrows Road crossing of the Childs River. Sub-watersheds to these stream discharge points allowed comparisons between field collected data from the streams 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 are reliable enough to calculate a pond-specific attenuation factor. Streamflow and associated surface water attenuation is included in the MEP nitrogen attenuation and freshwater flow investigation which is presented in Section IV.2.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to affect groundwater flow patterns (area and depth) is a standard part of the MEP data collection effort. In the present effort, eight freshwater ponds have delineated sub-watersheds within the Waquoit Bay Embayment watershed. 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.

Table IV-1. Percentage of unattenuated nitrogen loads in less than ten year time-of-travel sub-watersheds to Waquoit Bay/Eel Pond.

WATERSHED		LT10	GT10	TOTAL	%LT10
Name		kg/yr	kg/yr	kg/yr	
Eel Pond W	1	5,891		5,891	100%
Grassy Pond	2	42		42	100%
Childs R N GT10	3		1,099	1,099	0%
Fresh Pond Well	4	493		493	100%
Fresh Pond	5	149		149	100%
Childs R N LT10	6	2,902		2,902	100%
Childs R South	7	4,052		4,052	100%
Bournes Pond	8	121		121	100%
Seapuit River	9	158		158	100%
Eel Pond E	10	792		792	100%
Eel Pond S	11	191		191	100%
Waquoit Bay Main	12	483		483	100%
Sage Lot Pond	13	16		16	100%
Flat/Sage Lot Ponds Transition	14	239		239	100%
Flat Pond LT10	15	320		320	100%
Flat Pond GT10	16		430	430	100%
Jehu Pond LT10	17	912		912	100%
Jehu Pond GT10	18		516	516	0%
Great River LT10	19	132		132	100%
Great River GT10	20		104	104	0%
Lower Great River	21	1,104		1,104	100%
Red Brook LT10	22	2,248		2,248	100%
Red Brook GT10	23		677	677	0%
Lower Red Brook LT10	24	489		489	100%
Lower Red Brook GT10	25		58	58	0%
Hamblin Pond LT10	26	819		819	100%
Hamblin Pond GT10E	27		95	95	0%
Hamblin Pond GT10W	28		138	138	0%
Little River	29	400		400	100%
Lower Quashnet River	30	175		175	100%

Table IV-1 (continued). Percentage of unattenuated nitrogen loads in less than ten year time-of-travel sub-watersheds (FT10) to Waquoit Bay/Eel Pond.					
WATERSHED		LT10	GT10	TOTAL	%LT10
Name		kg/yr	kg/yr	kg/yr	
Middle Quashnet River LT10	31	721		721	100%
Middle Quashnet River GT10	32		116	116	0%
Upper Quashnet River LT10	33	3,995		3,995	100%
Upper Quashnet River GT10W	34		281	281	0%
Upper Quashnet River GT10N	35		970	970	0%
Moody Pond LT10	36		365	365	0%
Moody Pond GT10	37		731	731	0%
Johns Pond LT10	38	3,793		3,793	100%
Johns Pond GT10	39		1,653	1,653	0%
Ashumet Pond LT10	40		1,343	1,343	0%
Ashumet Pond GT10	41		1,431	1,431	0%
Weeks Pond LT10	42		87	87	0%
Weeks Pond GT10	43		20	20	0%
Snake Pond LT10	44		257	257	0%
Snake Pond GT10	45		16	16	0%
MMR J Well	46				0%
Mashpee Well No. 1	47	88		88	100%
Turner Road Well No. 5	48	108		108	100%
Waquoit Bay Embayment Whole System		30,833	10,386	41,219	75%
Notes: loads have been corrected to 1) include division of portions of nitrogen load from ponds and wellhead protection areas to down gradient sub-watersheds, 2) exclude nitrogen loads that are discharged outside of the Waquoit Bay Embayment system watershed from ponds or wellhead protection areas on the system watershed boundaries, and 3) ponds with LT10 time-of-travel watersheds above the estuary GT10 time-of-travel line are assigned to the GT10 column, 4) loads within the MMR J Well sub-watershed (#46) are removed from the system watershed by distribution of pumped water to the Massachusetts Military Reservation, 5) loads exclude atmospheric loading on the estuary surface waters; if these are included the percentage of load within less than 10 year time-of-travel increases to 78%. Note that this is an unrealistic worst case analysis, since most of the development more than 10 years travel time from the estuary has existed for more than 10 years, a refined analysis will show that on the order of 95% (or more) of the nitrogen sources within the watershed are contributing to the present water quality of bay waters.					

Based upon the evaluation of the watershed system, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for each sub-watershed that directly discharges 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 Waquoit Bay Embayment System; measurements were made to capture the spatial distribution of nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Since the watershed to the Waquoit Bay Embayment System includes portions of the towns of Mashpee, Falmouth, and Sandwich, the MEP Technical Team obtained digital parcel and tax assessor's data from each town to serve as a base for the watershed nitrogen loading model. Digital parcels and land use/assessors data from Falmouth are from 2009. Mashpee's data relies on the 2001 data collected for the East Waquoit MEP assessment (Howes, *et al*., 2005) updated with land use information developed by MEP staff and the Town's wastewater consultants for their current Watershed Nitrogen Management Plan (Eichner, *et al.*, 2011). Sandwich data (year 2000) also relies on information collected for the East Waquoit MEP assessment updated with more recent water use (discussed below) and new land-use data from the Mashpee Watershed Nitrogen Management Plan. These land use databases contain traditional information regarding land use classifications (MassDOR, 2009) plus additional information developed by the towns. This effort was completed with the assistance from GIS staff from the Cape Cod Commission (CCC).

Figure IV-1 shows the land uses within the Waquoit Bay Embayment System 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) open space, 8) public service/government (including road rights-of-way) 9) recreational (golf courses), and 10) properties without assessor's land use codes. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2009). "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (*e.g.*, wellfields, schools, open space, roads) and private groups like churches and colleges.

Public service land uses are the dominant land use type in the overall Waquoit Bay Embayment System watershed and occupy 48% of the watershed area (Figure IV-2). Examples of these land uses are lands owned by town and state government (including golf courses, open space, and wellhead protection lands), housing authorities, and churches. Residential land uses occupy the second largest area with 25% of the watershed area. It is notable that land classified by the town assessor as undeveloped is 11% of the overall watershed area. The Quashnet River and Flat Pond/Sage Lot Pond sub-watersheds are where most of the public service lands are; parcel examples in these sub-watersheds include the Massachusetts Military Reservation and South Cape Beach State Park, respectively.

In all the sub-watershed groupings shown in Figure IV-2, residential parcels are the dominant parcel type, ranging between 63% and 85% of the total parcels in these sub-watersheds and 74% of all parcels in the Waquoit Bay Embayment System watershed. Single-family residences (MassDOR land use code 101) are the dominant type of residential parcel; these generally represent 88% to 100% of residential parcels in the individual sub-watersheds and 98% of the residential parcels throughout the Waquoit Bay Embayment System watershed.

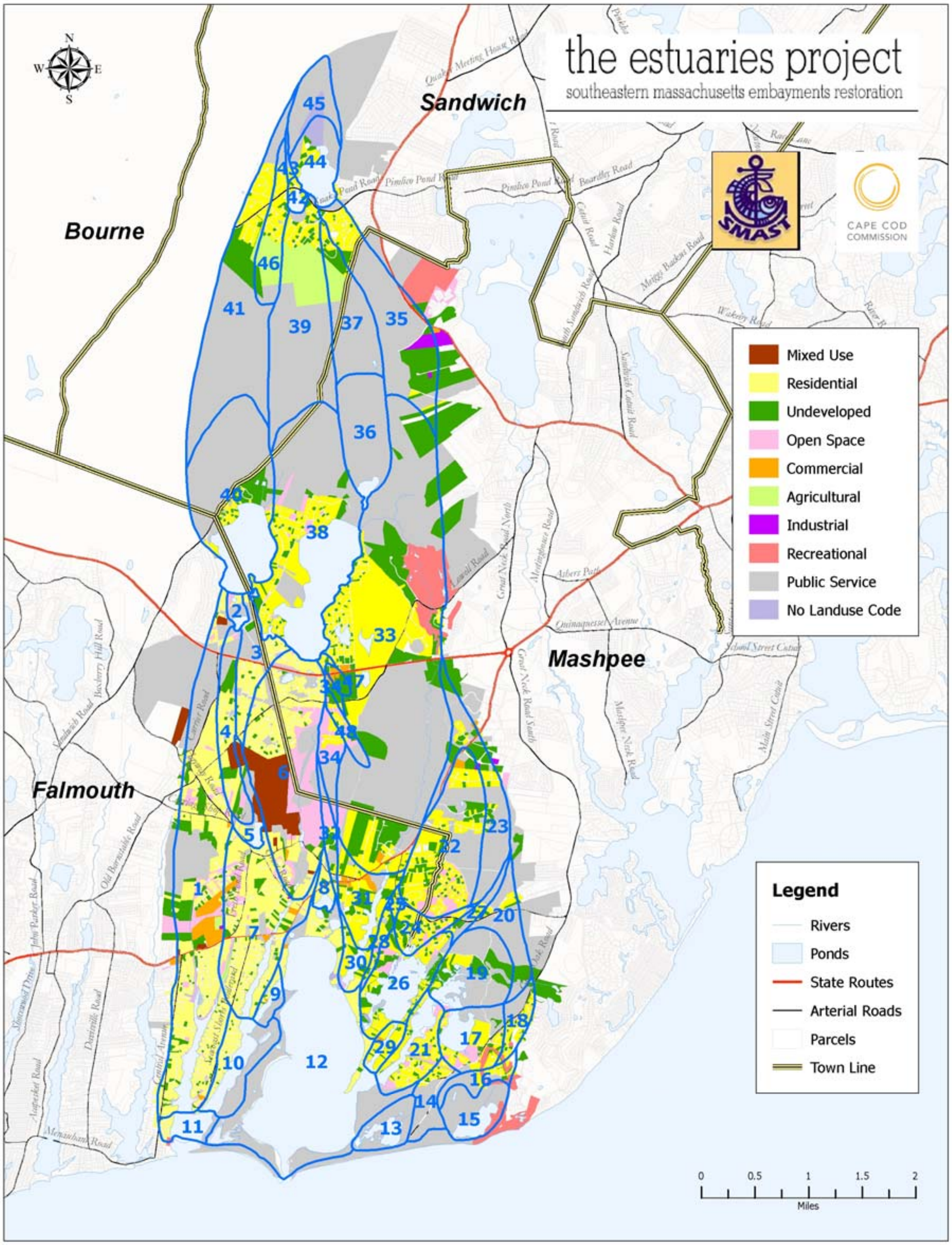


Figure IV-1. Land-use in the Waquoit Bay Embayment System watershed and component sub-watersheds. The watershed extends over portions of the Towns of Mashpee, Falmouth, and Sandwich. Land use classifications are based on respective town assessor classifications and MADOR (2009) categories. Base assessor and parcel data for Falmouth are from the year 2009, Mashpee's data are an updated version from year 2001, and Sandwich's data are an updated version from year 2000.

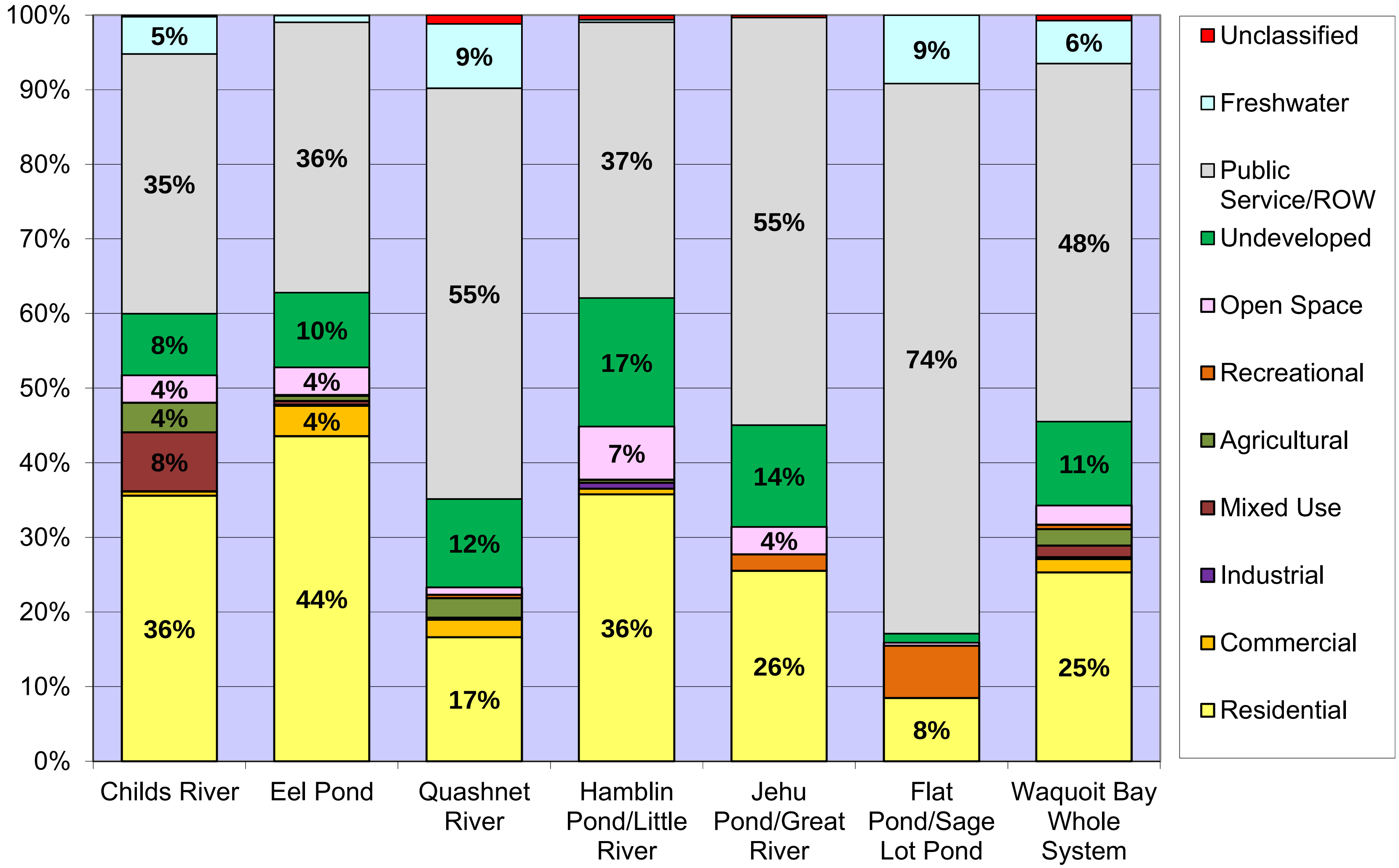


Figure IV-2. Distribution of land-uses by area within the Waquoit Bay Embayment System watershed and six component sub-watersheds. Land use categories are generally based on town assessor's land use classification and grouping recommended by MADOR (2009). Unclassified parcels do not have an assigned land use code in the town assessor's databases. Only percentages greater than or equal to 4% are shown.

In order to estimate wastewater effluent volumes discharged within the Waquoit Bay Embayment System watershed, MEP staff also obtained parcel-by-parcel water use data from the Towns of Falmouth, Sandwich, and Mashpee. Three years of water use (fiscal years 2008, 2009 and 2010 was obtained from the Town of Falmouth (personal communication, Bob Shea, GIS Coordinator, 11/10). The water use data were linked to the respective town parcel databases by the town GIS Department staff. During the preparation of the East Waquoit Bay MEP report (Howes, *et al.*, 2005), MEP staff obtained three years' worth of data (1997 – 1999) from the Mashpee Water District. This data are the basis for the town's current Watershed Nitrogen Management Plan (S&W, 2007). MEP staff discussed this data with Tom Fudala, Chair of the Mashpee Sewer Commission and Town of Mashpee Town Planner, and with Andrew Marks, Operations Manager, Mashpee Water District and the general consensus was that this dataset is still representative of water use in the Town of Mashpee. Consequently, this parcel-by-parcel water use dataset is used for the Mashpee portion of the Waquoit Bay Embayment with modifications that have occurred during the course of the Watershed Nitrogen Management Plan (*e.g.*, Eichner, *et al*., 2011). Three years of parcel-by-parcel water use (2007-2009) was obtained from the Sandwich Water District via the Cape Cod Commission; this data were linked to Sandwich parcels within the Waquoit Bay watershed by MEP staff.

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

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

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

All nitrogen losses within the septic system are incorporated into the MEP analysis. For example, information developed at the MassDEP Alternative Septic System Test Center at the

Massachusetts Military Reservation on Title 5 septic systems have shown nitrogen removals between 21% and 25%. Multi-year monitoring from the Test Center has revealed that nitrogen removal within the septic tank was small (1% to 3%), with most (20 to 22%) of the removal occurring within five feet of the soil adsorption system (Costa et al. 2001). Down gradient studies of septic system plumes in similar soils indicate that further nitrogen loss during aquifer transport is negligible (Robertson et al. 1991, DeSimone and Howes 1996).

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

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

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

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

The independent validation of the water quality model (Section VI) and the reasonableness of the freshwater attenuation (Section IV.2) add additional weight to the nitrogen loading coefficients used in the MEP analyses and a variety of other MEP embayments. While the MEP septic system nitrogen load is the best estimate possible, to the extent that it may underestimate the nitrogen load from this source reaching receiving waters provides a safety factor relative to other higher loads that are generally used for septic systems in regulatory situations. The lower concentration results in slightly higher amounts of nitrogen mitigation (estimated at 1% to 5%) needed to lower embayment nitrogen levels to a nitrogen target (*e.g.*, nitrogen threshold, cf. Section VIII). The additional nitrogen removal is not proportional to the septic system nitrogen level, but is related to 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 Waquoit Bay Embayment watersheds, MEP staff reviewed US Census population values for the Towns of Mashpee, Falmouth, and Sandwich. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. Based on data collected during the 2000 US Census, average occupancy within Falmouth is 2.36 people per housing unit with 69% of year-round occupancy of available housing units; 2010 Census results are roughly the same: 2.24 and 64%, respectively. Mashpee population numbers are similar: 2000 Census is 2.46 people per household with 63% year-round dwellings, while 2010 Census is 2.29 people per household with 62% year-round dwellings. Sandwich has much more year-round occupancy: 84% and 82% of housing units in Sandwich in the 2000 and 2010 US Census counts, respectively, are occupied year-round. The average people per household ratio is also higher in Sandwich, 2.75 and 2.66 in the 2000 and 2010 Census, respectively. Average water use for single-family residences with municipal water accounts in the Waquoit Bay Embayment MEP study area is 135 gpd. If this flow is multiplied by 0.9 to account for consumptive use, the study area wastewater average flow for a single-family residence is 122 gpd.

In order to provide a check on the measured water use, Mashpee, Falmouth, and Sandwich 2000 and 2010 Census average occupancies were used to estimate wastewater flows. Multiplying the respective 2000 Census town occupancies by the state Title 5 estimate of 55 gpd of wastewater per capita results in an average estimated water use per residence of 130 gpd, 136 gpd, and 151 gpd. Use of the 2010 Census occupancies results in similar flow estimates: 123 gpd for Falmouth, 126 gpd for Mashpee, and 146 gpd for Sandwich. These flows do not suggest that there is significant seasonal impacts on average water use in the Waquoit Bay Embayment watershed and that seasonal residences use water at a rate that approximate year-round water use. This analysis also 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 83% of the 5,621 developed parcels in the Waquoit Bay Embayment watershed. Parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (*e.g.*, 101 or 325), have been confirmed as having buildings on them through a review of aerial photographs, and do not have a listed account in the water use databases. Of the 941 developed parcels without water use accounts, 855 (91%) are classified as single-family residences (land use code 101). These parcels are assumed to utilize private wells and are assigned the Waquoit Bay Embayment study area average water use of 135 gpd in the watershed nitrogen loading modules. Another 65 developed parcels without water use are parcels classified as other types of residential properties (e.g., multi-family or condominiums). Given the preponderance of residential land uses among developed parcels without water use accounts, all developed parcels without water use are conservatively assigned 135 gpd as their water use in the watershed nitrogen loading model.

Wastewater Treatment Facilities and Alternative Septic Systems

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

MEP staff received a list of alternative, denitrifying septic system in Falmouth and Mashpee from the Barnstable County Department of Health and the Environment (personal communication, Brian Baumgaertel, 1/11). This list includes address and effluent monitoring data for selected systems. From the BCDHE database, project staff identified 68 denitrifying septic systems within the Mashpee portion of the Waquoit Bay Embayment watershed and 25 in the Falmouth portion with adequate total nitrogen monitoring data; a Sandwich list was not received. These systems all had three or more measurements of total nitrogen effluent concentrations; flow measurements are not collected at the same time so impacts of seasonality cannot be gauged. The average total nitrogen concentration for the Falmouth systems is 21.9 mg/l, while the average for the Mashpee systems is 15.3 mg/l. Individual sampling results ranged from 0.1 to 89.1 mg/l total nitrogen. The wastewater nitrogen loading factor for parcels with these systems was modified within the watershed nitrogen loading model to reflect the average total nitrogen concentrations in their effluent.

MEP staff also reviewed whether large wastewater treatment facilities discharge within the Waquoit Bay Embayment System watershed. Two state Groundwater Discharge Permits (GWDPs) are listed within the Waquoit Bay Embayment System watershed: Mashpee High School and Southport condominium complex. A GWDP is required under MassDEP regulations for wastewater treatment systems with design flows greater than 10,000 gallons per day. Data gathered during the East Waquoit MEP assessment was used to develop site-specific wastewater nitrogen loads for each of these facilities (Howes, *et al*., 2005) and these loads were incorporated into the watershed nitrogen loading model.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of watershed nitrogen loading to estuaries is usually fertilized areas: lawns, golf courses, and cranberry bogs. Residential lawns are usually the predominant source within this category. In order to add this source to the watershed nitrogen loading model for the Waquoit Bay Embayment system, MEP staff reviewed available regional information about residential lawn fertilizing practices and incorporated site-specific information for the following golf courses: Falmouth Country Club, Quashnet Valley, and New Seabury. An estimated nitrogen load is also included for the cranberry bogs and agricultural areas in the watershed. Cranberry bog nitrogen loading was determined based on previous studies conducted in southeastern Massachusetts. All of the golf courses were previously reviewed during other MEP assessments, previous fertilizer application information provided by the golf course superintendents was used to develop course-specific fertilizer application rates.

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

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

MEP staff obtained course- and turf-specific, nitrogen fertilizer application information for the three golf courses during the development of previous MEP assessments: Falmouth Country Club obtained completion of the Great, Green, and Bournes MEP assessment (Howes, *et al*., 2005b) and Quashnet Valley and New Seabury during the East Waquoit MEP assessment (Howes, *et al*., 2005a). Golf courses usually have different fertilizer application rates for different turf areas, usually higher annual application rates for tees and greens (~3 to 4 pounds per 1,000 square feet) and lower rates for fairways and roughs (~2 to 3.5 pounds per 1,000 square feet). As has been done in all MEP reviews, MEP staff reviewed the layout of all of the golf courses from aerial photographs, classified the various turf types, and, using GIS, assigned these areas to the appropriate sub-watersheds. The golf course-specific nitrogen application rates were then applied to the respective turf areas, a standard MEP 20% leaching rate was applied, and annual load for the portion of each golf course within each sub-watershed was calculated.

Nitrogen loads were also added for site-specific agricultural land uses. Cranberry bog fertilizer application rate and percent nitrogen attenuation in the bogs is based on an enhanced review of nitrogen export from cranberry bogs in southeastern Massachusetts (DeMoranville and Howes, 2009; Howes and Teal, 1995). Based on these studies, only the bog loses measurable nitrogen, the forested upland releases only very low amounts. For the watershed nitrogen loading analysis, the areas of active bog surface were digitized and checked against a GIS coverage maintained by MassDEP for Water Management Act purposes. The two cranberry bogs in the Waquoit Bay Embayment watershed are both located in the Quashnet River sub-watershed, and therefore nitrogen loss rates associated with flow through cranberry agriculture were used. Review of land use information also shows that there are also properties classified as having vegetable crops (MassDOR land use code 712); 85% of these lots are assumed to be fertilized. These properties are within the Ashumet, Johns, and Moody Ponds watersheds. Agricultural fertilizer rates developed in other MEP assessments (*e.g.*, Howes, *et al*., 2007) are used for these properties within the Waquoit Bay Embayment System watershed nitrogen loading model.

Nitrogen Loading Input Factors: Other

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

Road areas are based on MassHighway GIS information, which provides road width for various road segments. MEP staff utilized the GIS to sum these segments and their various widths by sub-watershed. Project staff also checked this information against parcel-based rights-of-way.

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information is linked to the parcel coverages, parcels are assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel is located within a respective sub-watershed. Following the assigning of boundary parcels, all large parcels are examined individually and are split (as appropriate) in order to obtain less than a 2% difference between the total land area of each sub-watershed and the sum of the area of the parcels within each sub-watershed. This effort results in "parcelized" watersheds that can be more easily used during the development of management strategies.

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. Building footprints, for example, is based on available information. Falmouth and Mashpee had building footprints within the land use databases used for this assessment, while Sandwich did not. Project staff used the average single-family residence building footprint based on available properties in the watershed (1,487 sq ft) for any residential units without footprint information. Commercial and industrial footprints for properties without building footprint information are also based on similar land uses within the Falmouth portion of the watershed. Individualized information for parcels with atypical nitrogen loading (condominiums, golf courses, etc.) is also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the Waquoit Bay Embayment system. 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.

Table IV-2. Primary Nitrogen Loading Factors used in the Waquoit Bay Embayment MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Mashpee, Falmouth, and Sandwich-specific data.

Nitrogen Concentrations:	**mg/l**	**Recharge Rates:**	**in/yr**
Road Run-off	1.5	Impervious Surfaces	40
Roof Run-off	0.75	Natural and Lawn Areas	27.25
Natural Area Recharge	0.072	**Water Use/Wastewater:**	
Direct Precipitation on Embayments and Ponds	1.09	Existing developed single-family residential parcels wo/water accounts and buildout residential parcels:	135 gpd[2]
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (sq ft)[1]	5,000	Existing developed parcels w/water accounts:	Measured annual water use
Residential Watershed Nitrogen Rate (lbs/lawn)[1]	1.08	Commercial and Industrial Buildings without/WU and buildout additions[3]	
Leaching rate	20%	Commercial	
Cranberry Bogs nitrogen release (kg/ha/yr)	6.9	Wastewater flow (gpd/1,000 ft2 of building):	74
Nitrogen Fertilizer Rate for golf courses, determined from site-specific information; other areas assumed to utilize residential application rate; vegetable crop nitrogen fertilizer applications based on loads determined in other MEP assessments		Building coverage:	15%
		Industrial	
		Wastewater flow (gpd/1,000 ft2 of building):	21
		Building coverage:	10%
		Average Single Family Residence Building Size from watershed data (sq ft)	1,487

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

Following the assignment of all parcels, sub-watershed modules were generated for each of the 48 sub-watersheds comprising the Waquoit Bay Embayment System watershed. These sub-watershed modules summarize, among other things: water use, parcel area, frequency, private wells, and road area. All relevant nitrogen loading data are assigned to each sub-watershed. Individual sub-watershed information is then integrated to create the Waquoit Bay

Embayment System Watershed Nitrogen Loading module with summaries for each of the individual 48 sub-watersheds. The sub-watersheds 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 Waquoit Bay Embayment System study area, the major types of nitrogen loads are: wastewater (*e.g*., septic systems), wastewater treatment facilities, fertilizers (including contributions from agriculture and golf courses), 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-3). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model.

One of these attenuation adjustments occurs in the freshwater ponds. Since groundwater outflow from a pond can enter more than one down gradient sub-watershed, the length of shoreline on the down gradient side of the pond is used to apportion the pond-attenuated nitrogen load to respective down gradient watersheds. The apportionment is based on the percentage of discharging shoreline bordering each down gradient sub-watershed. In the Waquoit Bay Embayment System study area, this occurs for ponds completely within the watershed (*e.g.*, Weeks Pond) and the ponds located along the outer boundary of the watershed (*e.g.*, Ashumet Pond). At Weeks Pond, for example, the pond has a down gradient shoreline of 1,181 feet; 70% of that shoreline discharges into the Johns Pond sub-watershed and 30% discharges to the MMR J Well sub-watershed. This breakdown of the water discharge from Weeks Pond means that 70% of the accompanying attenuated nitrogen load that leaves the pond reaches Johns Pond and the remainder is captured by the MMR J Well. Similar pond-specific calculations were completed wherever pond flows and nitrogen loads were divided among a number of down gradient receiving sub-watersheds.

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

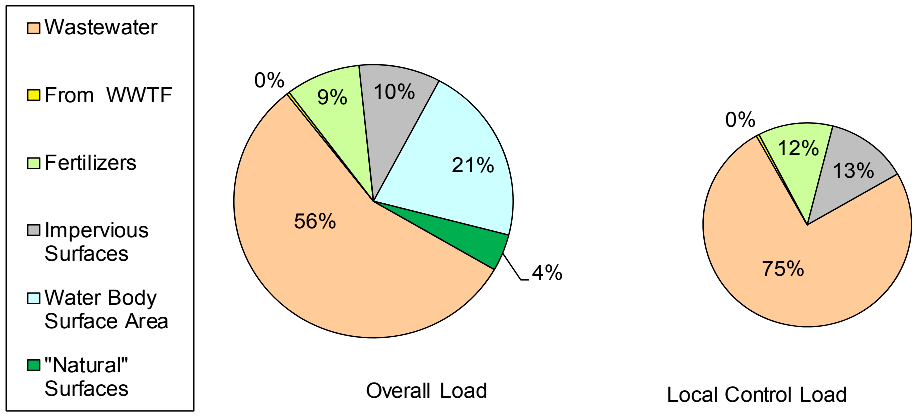
		Waquoit Bay N Loads by Input (kg/y):							% of Pond Outflow	***Present N Loads***			***Buildout N Loads***		
Watershed Name	**Watershed ID#**	**Wastewater**	**From WWTF**	**Fertilizers**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**		**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Waquoit Bay System		27,063	164	4,184	4,575	10,230	2,102	19,845		48,319		40,233	68,164		57,426
Bournes Pond	8	53	-	7	7	48	6	71		121		121	193	-	193
Seapuit River	9	130	-	14	8	-	6	31		158		158	189	-	189
Waquoit Bay Main	12	327	-	41	27	13	75	275		483		483	758	-	758
Waquoit Bay Main Estuary Surface						4,364				4,364		4,364	4,364	-	4,364
Childs River TOTAL		7,667	3	827	781	690	378	7,504		10,346		8,430	17,851	-	14,711
Childs R North Total		3,786	3	411	520	423	243	6,750		5,386	15%	3,877	12,136	15%	9,533
Childs R N LT10	6	2,363	-	239	134	24	143	6524		2,902		2,902	9,426	-	9,426
Childs R N GT10	3	937	-	79	54	1	29	71		1,099		1,099	1,171	-	1,171
Grassy Pond Total	GP	45	1	5	24	50	10	29	46%	134		38	163	-	48
Ashumet Pond Total	AP	51	1	5	27	39	9	22	4%	131		66	153	-	77
Johns Pond Total	JP	390	1	84	282	310	52	104	13%	1,119		456	1,223	-	493
Childs R South Total		3,881	0	415	261	267	136	754		4,960		4,553	5,715	-	5,178
Childs R South	7	3,392	-	367	213	-	80	510		4,052		4,052	4,562	-	4,562
Fresh Pond Total	FP	490	0	49	48	101	55	244	100%	743		336	987	-	451
Childs R South Estuary Surface						166				166		166	166	-	166
Eel Pond TOTAL		5,599	1	778	389	990	221	2,684		7,977		7,881	10,661	-	10,548
Eel Pond E	10	616	-	100	52	-	23	31		792		792	823	-	823
Eel Pond S	11	167	-	11	9	-	4	5		191		191	196	-	196
Eel Pond W Total		4,816	1	666	328	379	194	2,648		6,383		6,287	9,031	-	8,918
Eel Pond W	1	4,754	-	660	295	-	183	2617		5,891		5,891	8,509	-	8,509
Ashumet Pond Total	AP	43	1	4	23	33	7	19	3%	111		55	129		65
Grassy Pond Total	GP	19	0	2	10	21	4	12	19%	57		16	69		20
Eel Pond W Estuary Surface						325				325		325	325	-	325
Eel Pond E Estuary Surface						369				369		369	369	-	369
Eel Pond S Estuary Surface						242				242		242	242	-	242
Quashnet River TOTAL		6,870	160	1,506	2,711	2,421	995	7,011		14,663		8,589	21,674	-	14,189
Upper Quashnet River Total		6,174	160	1,439	2,638	2,207	941	6,795		13,559	15%	7,485	20,354	15%	12,870
Upper Quashnet River LT10	33	2,405	151	742	290	-	408	4044		3,995		3,995	8,038	-	8,038
Upper Quashnet River GT10W	34	199	-	25	33	-	23	125		281		281	406	-	406
Upper Quashnet River GT10N	35	613	-	53	213	-	91	1635		970		970	2,605	-	2,605
Moody Pond Total	MP	178	-	46	187	35	41	32	44%	487		244	519	-	260
Snake Pond Total	SP	25	-	2	2	100	14	3	28%	143		72	146		73
Johns Pond Total	JP	2,608	10	561	1,887	2,072	351	695	87%	7,488		3,050	8,183		3,302
Mashpee Well No. 1	47	63	-	0	21	-	4	197		88		88	285	-	285
Turner Road Well No. 5	48	84	-	9	5	-	10	64		108		108	171	-	171
Middle Quashnet River Total		556	-	53	61	122	44	190		837		837	1,027	-	1,027
Middle Quashnet River LT10	31	467	-	45	55	122	32	160		721		721	880	-	880
Middle Quashnet River GT10	32	89	-	8	6	-	12	31		116		116	147	-	147
Lower Quashnet River	30	139	-	13	12	-	10	25		175		175	200	-	200
Lower Quashnet River Estuary Surface						92				92		92	92	-	92

Table IV-3. Waquoit Bay Embayment Watershed Nitrogen Loads (continued).

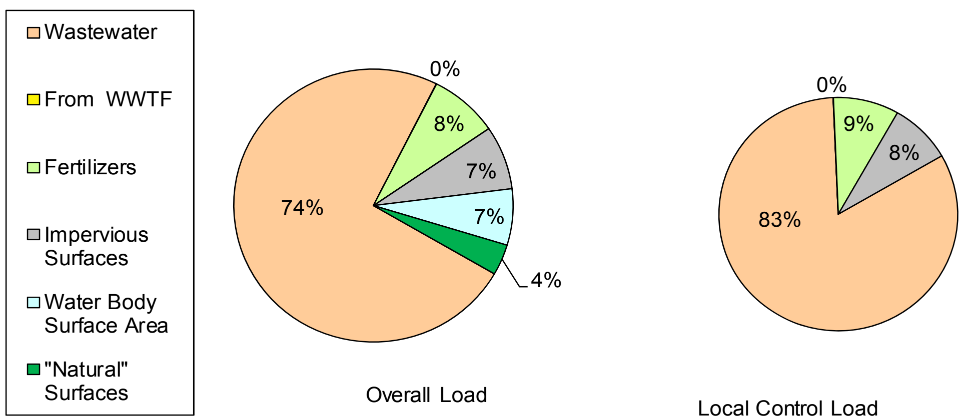
		Waquoit Bay N Loads by Input (kg/y):							% of Pond Outflow	***Present N Loads***			***Buildout N Loads***		
Watershed Name	**Watershed ID#**	**Wastewater**	**From WWTF**	**Fertilizers**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**		**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Hamblin Pond/Little River/Jehu Pond/Great River		6,003	-	712	605	1,358	352	1,937		9,030		9,030	10,967		10,967
Hamblin Pond/Little River TOTAL		3,973	-	346	370	635	215	1,651		5,538		5,538	7,190		7,190
Hamblin Pond TOTAL		3,650	-	309	336	578	208	1,524		5,081		5,081	6,605	-	6,605
Hamblin Pond LT10	26	660	-	71	59	-	29	250		819		819	1,069	-	1,069
Hamblin Pond GT10E	27	69	-	9	8	-	9	36		95		95	130	-	130
Hamblin Pond GT10W	28	108	-	9	14	-	7	20		138		138	159	-	159
Lower Red Brook LT10	24	370	-	39	42	20	17	127		489		489	616	-	616
Lower Red Brook GT10	25	43	-	6	7	-	2	10		58		58	68	-	68
Red Brook Total		2,401	-	175	206	-	144	1,080		2,925		2,925	4,006	-	4,006
Red Brook LT10	22	1,852	-	152	155	-	88	673		2,248		2,248	2,921	-	2,921
Red Brook GT10	23	549	-	23	51	-	56	408		677		677	1,085	-	1,085
Little River	29	322	-	36	34	-	7	127		400		400	527	-	527
Hamblin Pond Estuary Surface						558				558		558	558	-	558
Little River Estuary Surface						57				57		57	57	-	57
Jehu Pond/Great River TOTAL		2,031	-	366	234	723	138	286		3,492		3,492	3,777	-	3,777
Jehu Pond Total		1,054	-	240	96	246	38	112		1,675		1,675	1,787	-	1,787
Jehu Pond LT10	17	718	-	116	52	-	25	71		912		912	983	-	983
Jehu Pond GT10	18	336	-	123	44	-	13	41		516		516	557	-	557
Great River Total		116	-	15	25	202	81	56		438		438	494	-	494
Great River LT10	19	70	-	8	6	-	49	31		132		132	163	-	163
Great River GT10	20	46	-	7	18	-	32	25		104		104	129	-	129
Lower Great River	21	860	-	112	113	-	19	117		1,104		1,104	1,221	-	1,221
Jehu Pond Estuary Surface						246				246		246	246	-	246
Great River Estuary Surface						202				202		202	202	-	202
Lower Great River Estuary Surface						275				275		275	275	-	275
Flat Pond/Sage Lot Pond TOTAL		413	-	300	48	346	69	331		1,177		1,177	1,508	-	1,508
Sage Lot Pond	13	-	-	-	-	-	16	0		16		16	16	-	16
Flat/Sage Lot Ponds Transition	14	170	-	24	25	-	20	31		239		239	269	-	269
Flat Pond Total		243	-	277	23	174	33	301		750		750	1,051	-	1,051
Flat Pond LT10	15	-	-	123	-	174	23	0		320		320	320	-	320
Flat Pond GT10	16	243	-	154	23	-	11	301		430		430	731	-	731
Sage Lot Pond Estuary Surface						172				172		172	172	-	172

Table IV-3. Waquoit Bay Embayment Watershed Nitrogen Loads (continued).

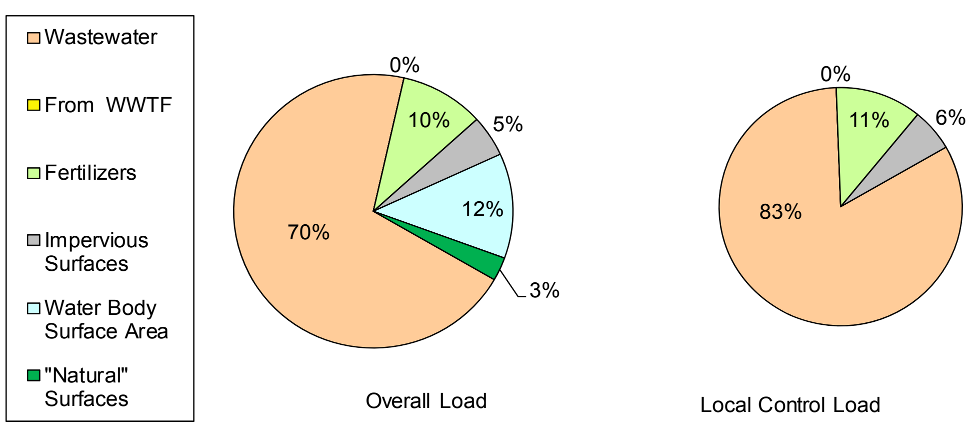
Freshwater Ponds		Waquoit Bay N Loads by Input (kg/y):							% of Pond Outflow	Present N Loads			Buildout N Loads		
Watershed Name	**Watershed ID#**	**Wastewater**	**From WWTF**	**Fertilizers**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**		**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Johns Pond Total	JP	2,998	11	645	2,169	2,382	403	799		8,607	50%	3,506	9,406	50%	3,796
Johns Pond LT10	38	1,360	-	157	671	1,498	105	235		3,793		3,793	4,027	-	4,027
Johns Pond GT10	39	453	-	336	786	-	77	127		1,653		1,653	1,780	-	1,780
Moody Pond Total	MP	222	-	57	234	44	52	40	56%	609		305	649	-	324
Snake Pond Total	SP	18	-	2	2	73	10	2	21%	104		52	106	-	53
Weeks Pond Total	WP	58	-	5	9	86	9	12	70%	166		68	178	-	74
Ashumet Pond Total	AP	886	11	88	466	681	150	383	70%	2,282		1,141	2,666	-	1,333
Moody Pond Total	MP	400	-	103	422	79	93	71		1,097	50%	548	1,168	50%	584
Moody Pond LT10	36	-	-	-	238	79	48	0		365		365	365	-	365
Moody Pond GT10	37	400	-	103	184	-	44	71		731		731	803	-	803
Ashumet Pond Total	AP	1,273	16	126	669	978	215	551		3,278	50%	1,639	3,829	50%	1,914
Ashumet Pond LT10	40	310	16	36	154	978	94	204		1,587		1,587	1,791	-	1,791
Ashumet Pond GT10	41	963	-	90	516	-	122	347		1,691		1,691	2,038	-	2,038
Weeks Pond Total	WP	82	-	7	13	122	13	17		237	50%	98	254	50%	106
Weeks Pond LT10	42	45	-	4	9	64	3	15		124		124	139	-	139
Weeks Pond GT10	43	23	-	1	3	-	2	0		29		29	29	-	29
Snake Pond Total	SP	15		1	1	59	8	2	17%	84		42	86		43
Snake Pond Total	SP	88		8	8	352	48	10		505	50%	253	515	50%	258
Snake Pond LT10	44	88	-	8	8	352	19	10		476		476	486	-	486
Snake Pond GT10	45	-	-	-	-	-	29	0		29		29	29	-	29
Grassy Pond Total	GP	98	1	10	51	109	21	62		291	50%	83	354	50%	104
Grassy Pond	2	2	-	0	0	35	5	20		42		42	62	-	62
Ashumet Pond Total	AP	97	1	10	51	74	16	42	8%	249		125	291	-	146
Fresh Pond Total	FP	490	0	49	48	101	55	244		743	50%	336	987	50%	451
Fresh Pond	5	64	-	7	4	63	11	5		149		149	155	-	155
Fresh Pond Well Total		426	0	42	43	38	44	239	100%	593		522	833	-	747
Fresh Pond Well Total		426	0	42	43	38	44	239		593		522	833	-	747
Fresh Pond Well	4	392	-	38	26	-	37	218		493		493	711	-	711
Grassy Pond Total	GP	34	0	3	18	38	7	21	34%	100		29	122	-	36
Removed from watershed by J Well															
MMR J Well Total		691		53	64	37	33			878		836	878		859
MMR J Well	46	667	-	51	60	-	29	20		807		807	827	-	827
Weeks Pond Total		25		2	4	37	4	5	30%	71		29	77		32



A. Whole System: Waquoit Bay/Eel Pond Estuary

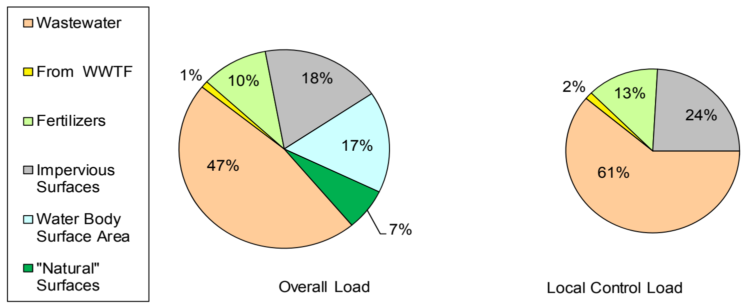


B. Childs River Subwatershed

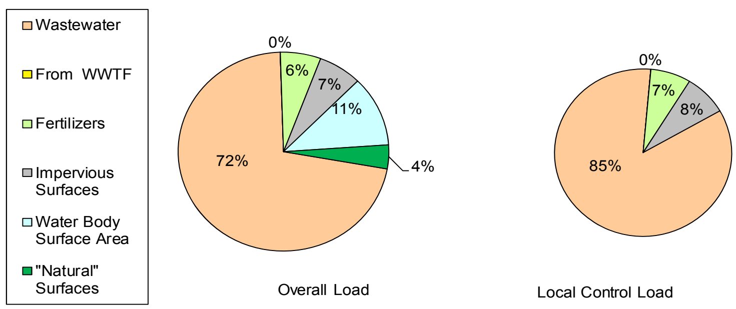


C. Eel Pond Subwatershed

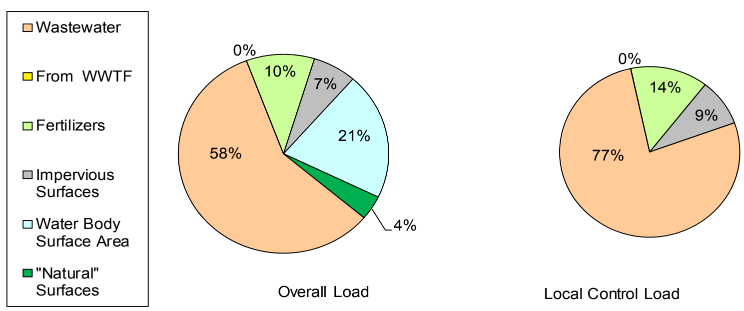
Figure IV-3 . Land use-specific unattenuated nitrogen loads (by percent) to the a) whole Waquoit Bay Embayment watershed, b) Childs River sub-watershed, and c) Eel Pond sub-watershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.



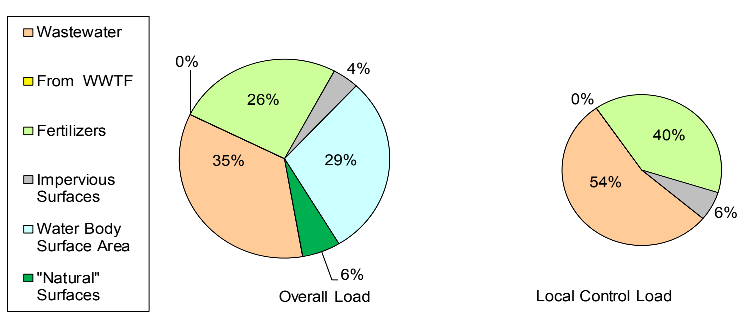
D. Quashnet River Subwatershed



E. Hamblin Pond/Little River Subwatershed



F. Jehu Pond/Great River Subwatershed



G. Flat Pond/Sage Lot Pond Subwatershed

Figure IV-3 (continued). Land use-specific unattenuated nitrogen loads (%) to the sub-watersheds: d) Quashnet River, e) Hamblin Pond/Little River, f) Jehu Pond/Great River, and g) Flat Pond/Sage Lot Pond. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be managed under local regulatory control.

Freshwater Pond Nitrogen Loads

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

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

Bathymetric information is generally a prerequisite for determining enhanced attenuation, since it provides the volume of the pond and, with appropriate pond 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.

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

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

Within the Waquoit Bay Embayment System watershed, there are eight freshwater ponds with delineated watersheds: Weeks, Grassy, Fresh, Ashumet, Snake, Moody, Johns, and Bournes. Most of these ponds have been sampled multiple times during the nine years that PALS Snapshots have been conducted, but among these ponds, only Ashumet, Johns, and Snake have available pond-wide bathymetric data (Eichner, *et al*., 2003). Among these three ponds, only Ashumet has had sufficient sampling to assign a pond-specific nitrogen attenuation rate and this data supports the use of a 50% attenuation rate. As such, a reasonable pond-specific nitrogen attenuation rate cannot be developed for the other fresh ponds within the Waquoit Bay Embayment System watershed, except for Ashumet Pond. All ponds with delineated sub-watersheds were assigned the standard MEP freshwater pond nitrogen attenuation rate of 50% in the watershed nitrogen loading model.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development and accompanying nitrogen loads within the study area watersheds. The MEP buildout is relatively straightforward and is generally completed in four steps: 1) each residential parcel classified by the town assessor as developable is identified and divided by minimum lot sizes specified in town zoning and the resulting number of new residential units is rounded down, 2) parcels classified as developable commercial and industrial parcels by the town assessor are identified, 3) residential, commercial and industrial parcels with existing development and areas greater than twice zoning's minimum lot size are identified, divided by the minimum lot size and the resulting number of new units is rounded down, and 4) results are discussed with town staff and/or planning board members and the analysis results are modified based on local knowledge.

It should be noted that the initial MEP buildout approach is relatively simple and does not include any modifications/refinements for lot line setbacks, wetlands, road construction, frontage requirements, parcel shape requirements, or other more detailed zoning provisions. The MEP buildout approach also does not include potential impacts associated with the higher densities usually associated with 40B affordable housing projects. The fourth step, including the discussions with town planners, and, occasionally, town planning boards and wastewater consultants, usually leads to additional insights on developments that are planned, especially developments planned on government or public service parcels, and updates to assessor classifications, including lands purchased by the town as open space. This final step may lead to removal and/or additions to the number of parcels initially identified as developable and may include application of more detailed zoning provisions.

As an example of how the MEP approach might apply, assume an 81,000 square foot lot is classified by the town assessor as a developable residential lot (land use code 130). This lot is divided by the 40,000 square foot minimum lot size specified in town zoning and the result is rounded down to two. As a result, two additional residential lots would be added to the sub-watershed in the MEP buildout scenario. This addition could then be modified during discussion of town staff.

Other provisions of the MEP buildout assessment include undevelopable lots, commercial and industrial properties, and lots less than the minimum areas specified by zoning. Properties classified by the Town of Mashpee, Falmouth, and Sandwich assessors as “undevelopable” (*e.g.*, MassDOR codes 132, 392, and 442) are not assigned any development at buildout (unless revised by the town review). Commercial and industrial properties classified as developable are not subdivided; the area of each parcel and the factors in Table IV-2 are used to determine a building size and wastewater flow for these properties. Pre-existing lots classified by the town assessor as developable are also treated as developable even if they are less than the minimum lot size specified in zoning; so, for example, a 10,000 square foot lot classified by the town assessor as a developable residential property (130 land use code) will be assigned an additional residential dwelling in the MEP buildout scenario even though the minimum lot size required by the zoning in the area is 40,000 square feet. Most town zoning bylaws have a lower minimum lot size for pre-existing lots (usually 5,000 square feet) that will minimize instances of regulatory takings. Existing developed residential properties that are larger than zoning’s minimum lot sizes are also assigned additional development potential only if enough area is available to accommodate at least one additional lot as specified by the zoning minimum.

Following the completion of the initial buildout assessment for the Waquoit Bay Embayment System watersheds, MEP staff reviewed the results with town officials. MEP staff reviewed the preliminary Falmouth buildout results with Brian Currie, Falmouth Town Planner in April 2011. The buildout results for the Mashpee and Sandwich portions of the watershed were reviewed during the previous buildout assessment of the East Waquoit MEP watershed (Howes, *et al*., 2005a). These buildout results were updated based on the Town of Mashpee work on their Watershed Nitrogen Management Plan (S&W, 2007) and subsequent updates completed for the town by MEP staff (Eichner, *et al.*, 2011). Suggested changes from all reviews were incorporated into the final buildout for Waquoit Bay/Eel Pond.

All the parcels with additional buildout potential within the Waquoit Bay Embayment watershed are shown in Figure IV-4. 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. Buildout additions within the Waquoit Bay Embayment System watersheds will increase the unattenuated loading rate by 41%.

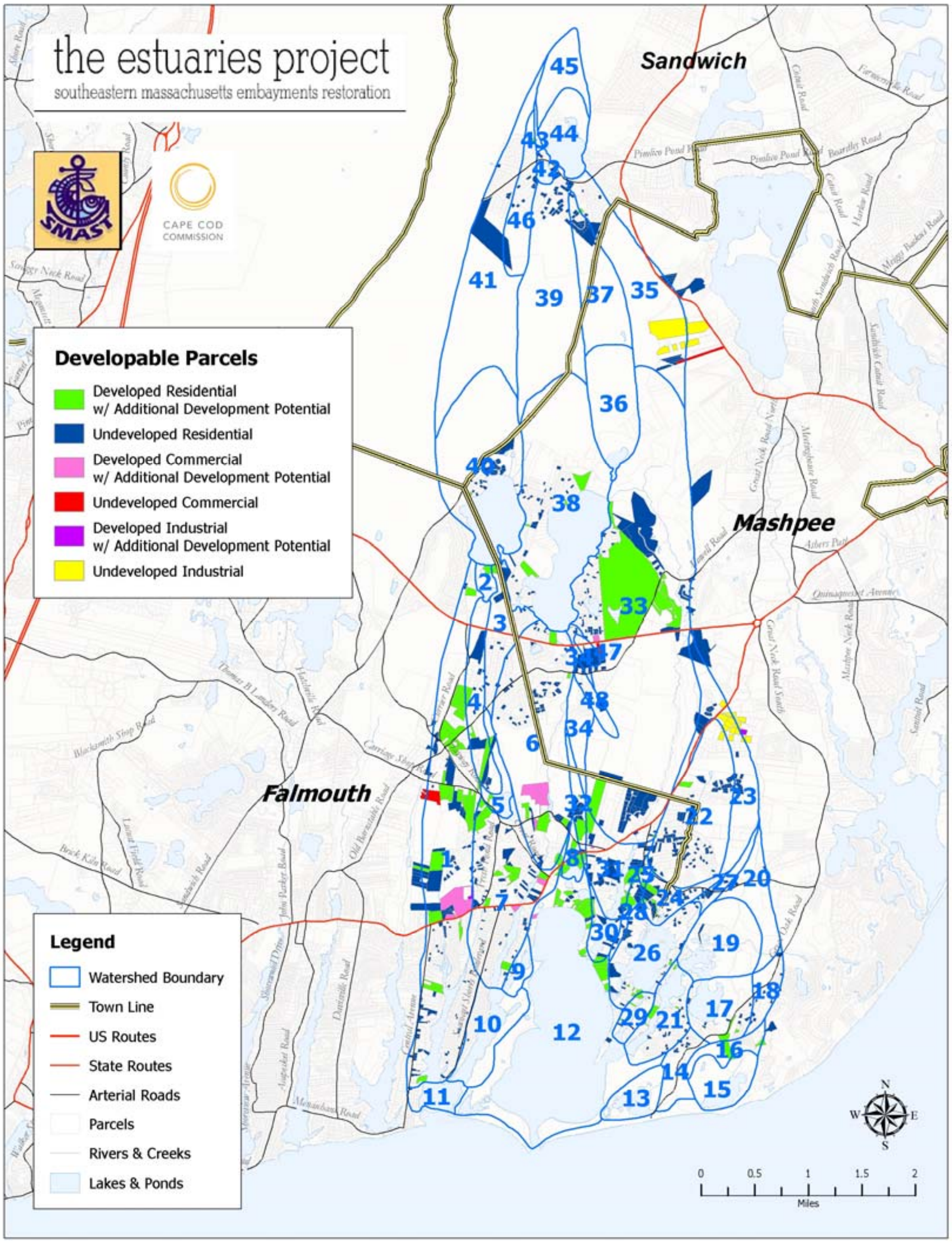


Figure IV-4. Developable Parcels in the Waquoit Bay Embayment System watershed. Parcels colored green, pink, and purple are developed parcels (residential, commercial and industrial, respectively) with additional development potential based on current zoning, while parcel colored blue, red, and yellow are corresponding undeveloped parcels classified as developable by the town assessor and represent 11% of the watershed area. Parcels along watershed boundaries are assigned to sub-watersheds 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 town zoning; these parcels are assigned estimated nitrogen loads in MEP buildout calculations. All buildout results were reviewed with town staff.

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 or sewering analysis) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the sub-watersheds of each sub-embayment (Eel Pond / Childs River, Hamblin Pond, Jehu Pond and Quashnet River) of the overall Waquoit Bay embayment system 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 is through groundwater in sandy outwash aquifers. 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 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 which 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. Within the Waquoit Bay System Watershed a significant portion of freshwater flow and transported nitrogen passes through a surface water system and frequently multiple systems, producing the opportunity for significant nitrogen attenuation.

Failure to determine the attenuation of watershed derived nitrogen overestimates the nitrogen load to receiving waters. If nitrogen attenuation is significant in one portion of a watershed and insignificant in another the result is that nitrogen management would likely be more effective in achieving water quality improvements if focused on the watershed region having unattenuated nitrogen transport (other factors being equal). In addition to attenuation by freshwater ponds (see Section IV.1.3, above), attenuation in surface water flows is also important. An example of the significance of surface water nitrogen attenuation relating to embayment nitrogen management was seen in the Agawam River, where >50% of nitrogen originating within the upper watershed was attenuated prior to discharge to the Wareham River Estuary (CDM 2001). Similarly, in a preliminary study of Great, Green and Bournes Ponds in Falmouth, measurements indicated a 30% attenuation of nitrogen during stream transport (Howes and Ramsey 2001). An example where natural attenuation played a significant role in nitrogen management can be seen relative to West Falmouth Harbor (Falmouth, MA), where ~40% of the nitrogen discharge to the Harbor originating from the groundwater discharge from the WWTF was attenuated by a small salt marsh prior to reaching Harbor waters. Similarly, the small tidal basin of Frost Fish Creek in the Town of Chatham showed ~20% nitrogen attenuation or watershed nitrogen load prior to discharge to Ryders Cove. Clearly, proper development and evaluation of nitrogen management options requires determination of the nitrogen loads reaching an embayment, not just loaded to the watershed.

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements were undertaken as part of the MEP Approach. MEP conducted a study on natural attenuation relating to several sub-embayments of the overall Waquoit Bay System in addition to the natural attenuation measures by fresh kettle ponds, addressed above. The additional site-specific study was conducted in the major surface water flow systems, (i.e. the Quashnet River discharging to the tidal portion of the Quashnet River sub-embayment and the Childs River discharging to the eastern branch of Eel Pond). These rivers carry a large proportion of the freshwater inflow to the Waquoit Bay System, so that it provides a significant check on the nitrogen loading rate to this entire system.

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 Quashnet River (at Route 28) provided a direct integrated measure of all of the processes presently attenuating nitrogen in the sub-watersheds up-gradient from the gauging sites. Similarly, the flow in Childs River was measured at the Barrows Road crossing (Figure IV-5). The upper watershed regions for each of these surface water features account for more than half of the entire watershed area to the eastern and western Waquoit Bay System. Flow and nitrogen load were measured at the gauging sites for 16 months of record (Figure IV-7, IV-8, IV-9). During study period, velocity profiles were completed on the rivers every month to two months. Periodic measurement of flows over the entire stream gauge period of record allowed for the development of a stage-discharge relationships (rating curve). These relationships were then used to obtain flow volumes from the continuously record of stream stage. In the case of the Quashnet River, stream stage was measured by the US Geological Survey. At the start of the MEP nutrient threshold analysis of the Quashnet River sub-embayment to Waquoit Bay, a stream gauge was deployed proximal to the USGS gauging station. Though the USGS has been collecting river stage continuously since 1988, the MEP chose to deploy a stream gauge in the same location as the USGS in order to confirm the accuracy of MEP stage measurements relative to an independent measure. The gauge was deployed in June of 2002 and measured at a 10-minute frequency until the first week of August 2002 when it was stolen. A second gauge was not deployed due to the likelihood of theft or vandalism. The MEP Technical Team concluded that using the USGS stage data, in conjunction with an MEP developed rating curve for the Quashnet River, would yield satisfactory results and enable the MEP to meet its objectives of accurately determining nitrogen attenuation within the Quashnet River watershed. Though only a short term (June 2002 – August 2002) stage record was measured by the MEP for the Quashnet River, a comparison of MEP measured stage to the USGS measured stage was still possible and showed that both stage records agreed well. Both stage records showed similar peaks and magnitude of peaks indicating that the MEP gauge was functioning as an accurate measure of river stage. For the Childs River the MEP Technical Team deployed and maintained a stream gauge and utilized the measured stage at the gauge to calculate daily flow from the MEP developed rating curve.

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

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

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

where by:

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

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

Periodic measurement of flows over the entire stream gauge deployment period allowed for the development of a stage-discharge relationship (rating curve) that could be used to obtain flow volumes from the detailed record of stage measured by the continuously recording stream gauges. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given river/stream/creek/brook. These hourly stages values where then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. In the case of tidal influence on stream stage, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of strictly freshwater flow. The lowest low tide stage values for any given day were utilized in the stage – discharge relation in order to compute daily flow as this stage value is most representative of freshwater flow.

A complete annual record of stream flow (365 days) was generated for the Quashnet River (USGS stage record) and the Childs River (MEP stage record). The annual flow record for each surface water system was merged with the nutrient data sets generated through the weekly water quality sampling to determine nitrogen loading rates to the tidally influenced portion of the Quashnet River and Childs River.

IV.2.2 Surface Water Discharge and Attenuation of Watershed Nitrogen: Quashnet River to Quashnet River Estuary

John's Pond (and an associated network of down stream cranberry bogs) is one of the larger ponds within the study area and unlike many of the freshwater ponds, John's Pond has stream outflow rather than discharging solely to the aquifer on the down-gradient shore. This stream outflow, the Quashnet River, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands and stream bed associated with the Quashnet River. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the Quashnet River above the gauge site and the measured annual discharge of nitrogen to the tidal portion of the Quashnet River, Figure IV-5.

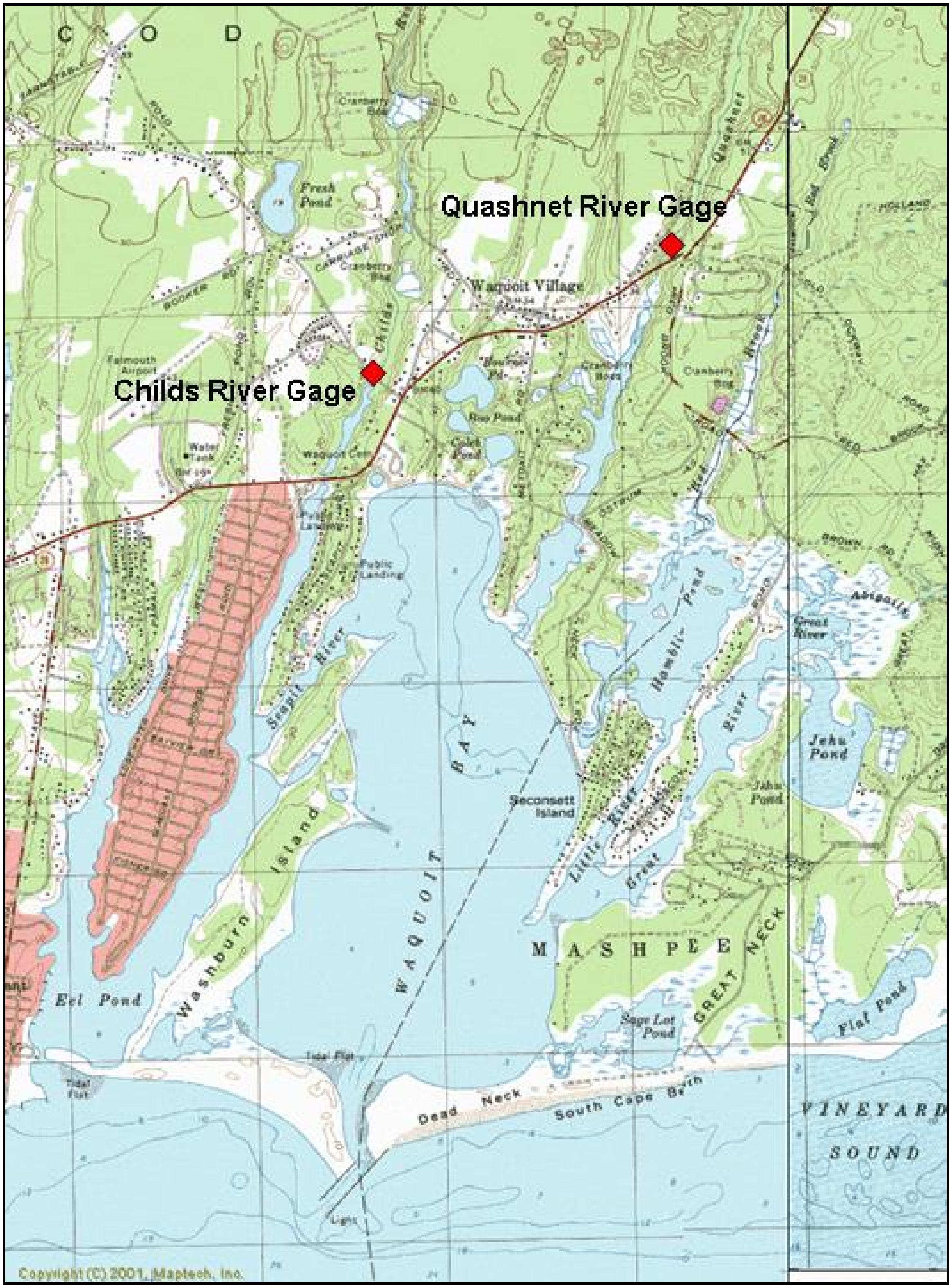


Figure IV-5. Location of Stream gauges (red symbol) in the Childs River and Quashnet River sub-embayments to the Waquoit Bay system.

A water quality sampling station was established at the USGS stream gaging location within the outflow stream (Quashnet River) from John's Pond, which is also fed by groundwater inflow within its lower reaches Quashnet River (primarily sub-watershed #6, Figure IV-4). A rating curve was developed for the cross section of the Quashnet River that is situated up-gradient of Route 28 prior to the discharge of the Quashnet River into the tidally influenced portion of the Quashnet River as depicted in Figure IV-5.

River flow (volumetric discharge) was measured monthly using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Quashnet River site based upon these measurements and measured water levels at the USGS 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. These measurements allowed for the determination of both total volumetric discharge and nitrogen mass transport to the estuarine portion of the Quashnet River (Figure IV-7, Figure IV-8, Table IV-4 and Table IV-5). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at the gauge site (Figure IV-6). Comparison of measured and predicted discharge is used to confirm that the stream is capturing the entire recharge to its up-gradient contributing area. This comparison also can be used as a check on the watershed area, although it is limited in that the stream flow estimate from the watershed area is a long-term average and the MEP gauge estimate is over 12-16 months. In the MEP study, the 2 estimates were only 9% apart (i.e. good agreement). This freshwater balance is also important for supporting the nitrogen attenuation calculations.

The final stream gauge record available for this analysis of freshwater stream flow and associated attenuated nitrogen load covers a period of 365 days for the discharge of the Quashnet River to the tidally influenced portion of the lower Quashnet River prior to discharge to Waquoit Bay. Using the available flow measurements, a stream flow record for a complete year was constructed for the freshwater portion of the Quashnet River from which annual and average daily freshwater flow to the Quashnet River Estuary was determined (Figures IV-7 and IV-8 and Table IV-4). The annual freshwater flow record for the Quashnet River, as developed using USGS measured stage and the rating curve (stage – discharge relation) developed by the MEP, was compared to the modeled flows as determined by the USGS and was found to be within two percent of each other indicating excellent agreement (Table IV-5).

Total nitrogen concentrations within the Quashnet River outflow were relatively high, 0.497 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 20,658 g/day (20.66 kg/d) and a measured total annual TN load of 7,540 kg/yr. In the Quashnet River, nitrate was the predominant form of nitrogen (41%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the pond or stream ecosystems. The high concentration of inorganic nitrogen in the outflowing stream waters also suggests that plant production within the up-gradient freshwater ecosystems is not nitrogen limited.

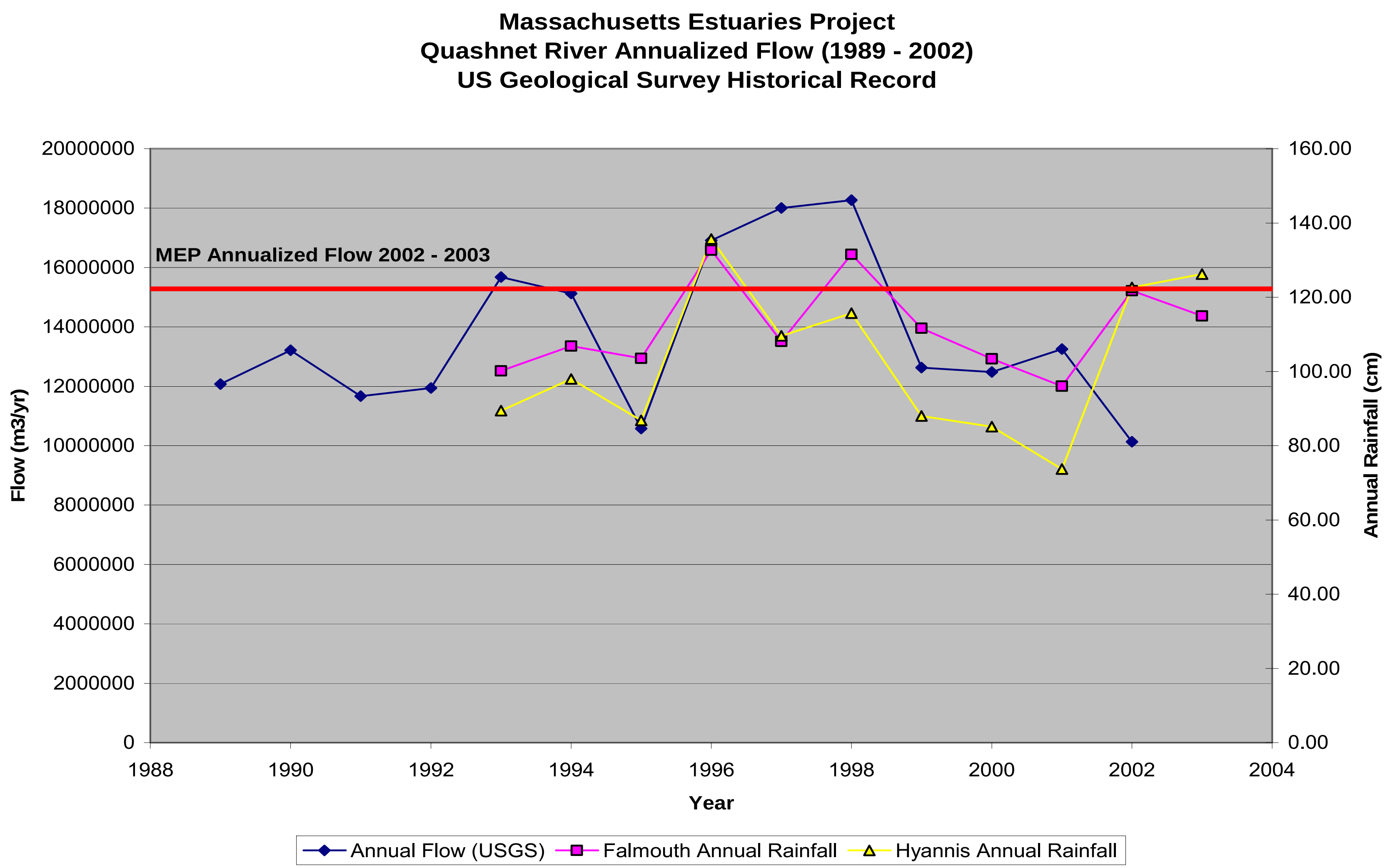


Figure IV-6. Comparison of historical Quashnet River flows as determined by the US Geological Survey (1989 – 2002) and the annualized flow developed by the MEP (2003) all relative to annual rainfall from meteorological stations in Falmouth and Hyannis, MA.

Table IV-4. Comparison of water flow and nitrogen discharges from the Quashnet River to the lower estuarine reach of the Quashnet River. The "Stream" data are from the MEP stream gauging effort. Watershed data are based on the MEP watershed modeling effort by the USGS.

Stream Discharge Parameter	Discharge Quashnet River to Waquoit Bay[b] (MEP)	Discharge Quashnet River to Waquoit Bay (USGS)	Data Source
Total Days of Record[a]	365	365	(1)
Flow Characteristics			
Stream Average Discharge (m3/day)	41529	40712 / 46485	(1) / (2a,2b)
Contributing Area Average Discharge (m3/day)	45752	45752	(3)
Proportion Discharge Stream vs. Contributing Area (%)	9%	11% / 2%	
Nitrogen Characteristics			
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.204	0.204	(1)
Stream Average Total N Concentration (mg N/L)	0.497	0.498	(1)
Nitrate + Nitrite as Percent of Total N (%)	41%	41%	(1)
Total Nitrogen (TN) Average Measured Stream (kg/d)	20.66	20.29	(1)
TN Average Contributing Area UN-attenuated Load (kg/d)	37.15	37.15	(4)
Attenuation of Nitrogen in Pond/Stream (%)	44%	45%	(5)

[a] from September 10, 2002 to September 10, 2003
[b] Flow and N load to Quashnet River including John's Pond Contributing Area

(1) MEP developed stream rating curve and nutrient data used in conjunction with USGS stage data.
(2a) USGS flow data 1989-2002.
(2b) USGS flow data 2002-2010
(3) Calculated from MEP watershed delineations to John's Pond; the fractional flow path from each sub-watershed which contribute to Quashnet River; and the annual recharge rate. This watershed based average discharge is 2% smaller than what was previously reported in the MEP in 2005 due to a refinement to the John's Pond watershed.
(4) As in footnote #3, with the addition of pond and stream conservative attenuation rates.
(5) Calculated based upon the measured TN discharge from the river vs. the unattenuated watershed load.

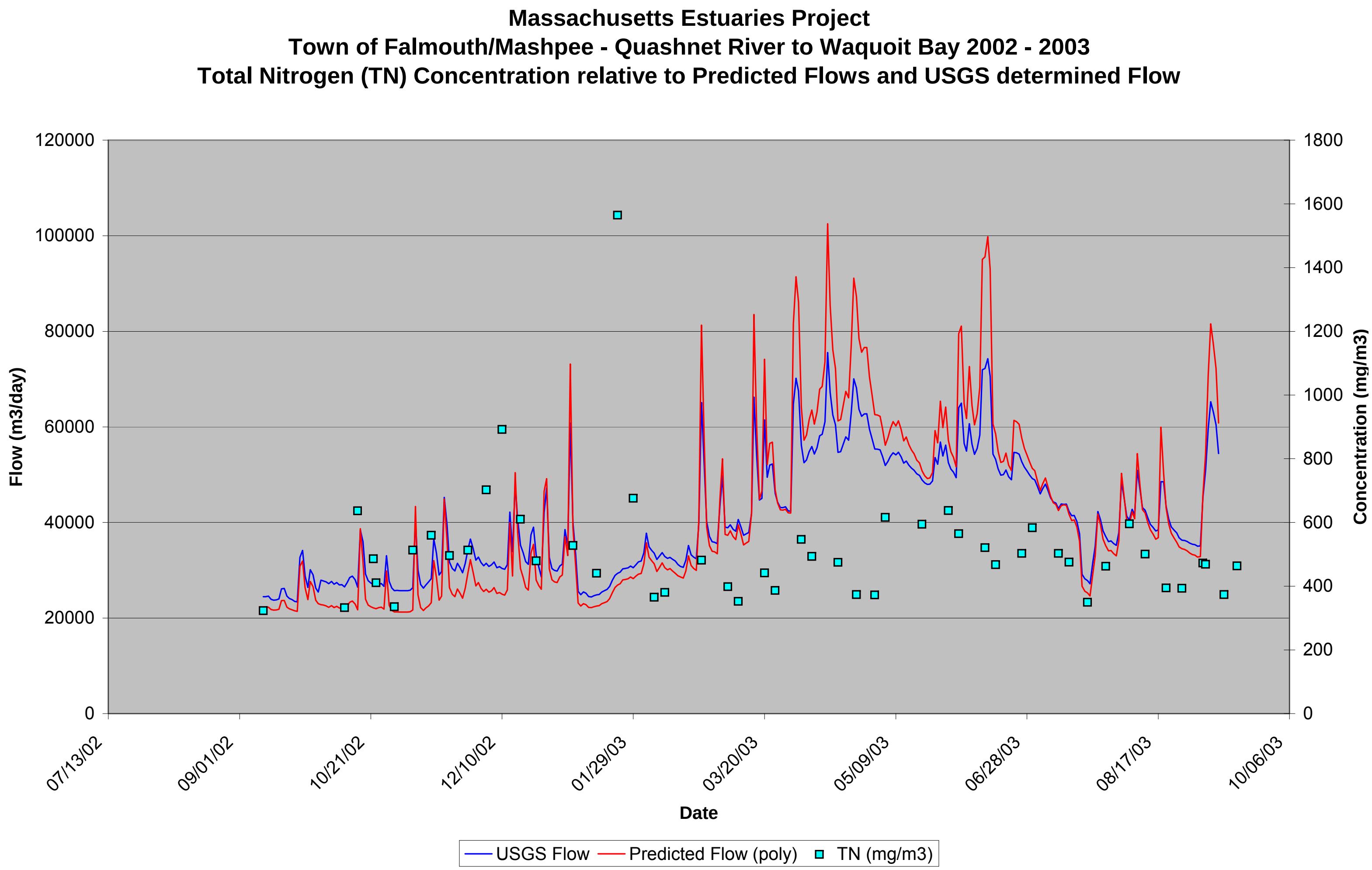


Figure IV-7. Quashnet River annual discharge developed from a stream gauge maintained above the tidal reach of the lower Mashpee River estuarine waters. Nutrient samples were collected weekly and analyzed for inorganic and organic nitrogen species. These data were used to determine both annual flow and total nitrogen transport for determining nitrogen attenuation (see Table IV-4).

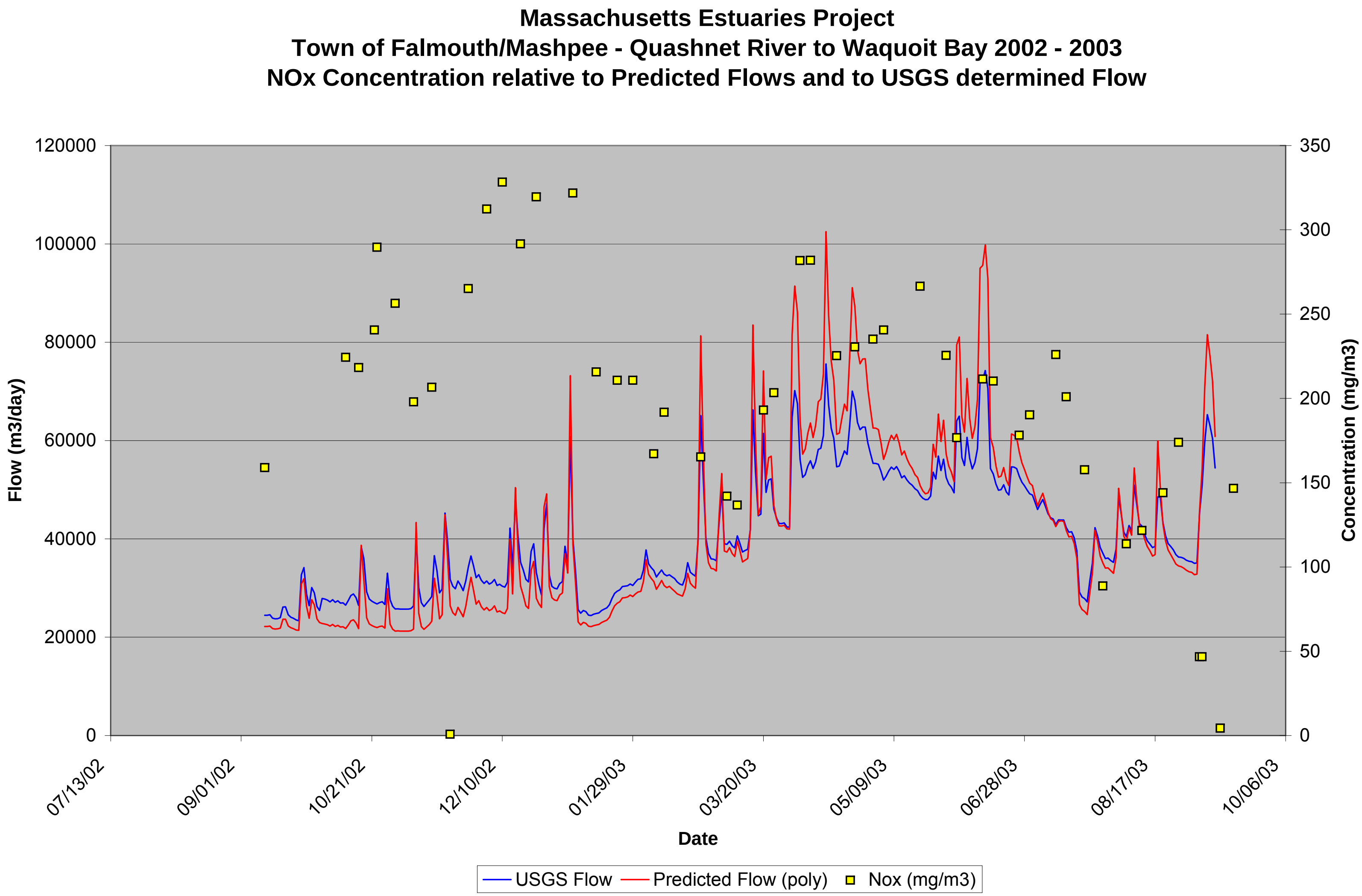


Figure IV-8. Nitrate + Nitrite (Nox) concentration and Quashnet River annual discharge developed from a stream gauge maintained in the outflow from John's Pond discharging to tidally influenced portion of Quashnet River. Nutrient samples were collected approximately weekly and analyzed for inorganic and organic nitrogen species. These data were used to determine both annual flow and total nitrogen transport for determining nitrogen attenuation (see Table IV-4).

Table IV-5. Summary of Flow and Nutrient loads from both the Quashnet River discharging to tidally influenced Quashnet River estuarine reach.

SYSTEM	PERIOD	DISCHARGE (m3/yr)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
QUASHNET RIVER	(MEP) September 10, 2002 to September 10, 2003	15151967	3088	7540
QUASHNET RIVER	(USGS) September 10, 2002 to September 10, 2003	14860060	3028	7407
QUASHNET RIVER	(CCC) Based on 27.25 in./yr recharge and watershed	16699480		

From the measured nitrogen load discharged by the Quashnet River to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is significant nitrogen attenuation of upper watershed derived nitrogen during transport to the Bay. Based upon lower nitrogen load (20.66 kg N d^{-1}, 7540 kg yr^{-1}) discharged from the freshwater Quashnet River and the nitrogen mass entering from the associated watershed (37.15 kg N d^{-1}, 13,559 kg yr^{-1}) the integrated measure of nitrogen attenuation by the pond/river ecosystem is 44%. The directly measured nitrogen loads from the Quashnet River was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Childs River Discharge to the East Branch of Eel Pond

John's Pond (and an associated network of down stream cranberry bogs) is one of the larger ponds within the study area and unlike many of the freshwater ponds, John's Pond has stream outflow rather than discharging solely to the aquifer on the down-gradient shore. This stream outflow, the Childs River along with the Quashnet River, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands and stream bed associated with the Childs River. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the Childs River above the gauge site and the measured annual discharge of nitrogen to the tidal portion of the Childs River, Figure IV-5.

The freshwater flow carried by the Childs River to the estuarine waters of the East Branch of Eel Pond was determined using a continuously recording vented calibrated water level gauge. As this surface water system was potentially tidally influenced, the discharge from Childs River at the gauge location was checked to confirm the extent of tidal influence and whether freshwater flow could be measured at low tide in the estuary. To confirm that freshwater was being measured, salinity measurements were conducted on weekly water quality samples collected from the gauge site. Average measured sample salinity at low tide was found to be 0.1 ppt, indicating no tidal influence at the gauge location at low tide. As such, no salinity adjustment was made to the flows in order to determine daily freshwater flows using the MEP developed stage-discharge relation. The Childs River gauge location was deemed acceptable for making flow measurements and obtaining an estimate of annual freshwater flow. Calibration of the gauge was checked monthly. The gauge was installed on May 26, 2006 and was set to operate continuously for 16 months such that at least one summer season would be captured in the flow record. Stage data collection continued until March 10, 2008 for a total deployment of 20 months.

Flow in the Childs River (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the gauge site based upon these flow measurements and the measured water levels at the gauge site. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge to the head of the East Branch of Eel Pond (western sub-embayment connected to Waquoit Bay via Seapit River). The integrated measure of nitrogen mass discharge at the top of the Eel Pond sub-embayment is reflective of the biological processes occurring in John's Pond, the channel bed of the river, wetlands and wooded areas all of which contribute to nitrogen attenuation (Figure IV-9 and Table IV-6, IV-7). In addition, a water balance was constructed based upon the U.S. Geological Survey/MEP refined watershed delineations to determine long-term average freshwater discharge expected at the Childs River gauge site based on area and average recharge.

The annual freshwater flow record for the Childs River as measured by the MEP was compared to the long-term average flows determined by the USGS/MEP modeling effort (Table III-1). The measured freshwater discharge from the Childs River down gradient of Barrows Road was 9.7% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for the hydrologic year beginning September 2006 and ending in August 2007 (low flow to low flow) was 10,372 m^3/day compared to the long term average flows determined by the watershed modeling effort (11,492 m^3/day). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Childs River discharging from the sub-watershed indicate that the river is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Childs River outflow were relatively low, 0.258 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 10.51 kg/day and a measured total annual TN load of 3,835 kg/yr. In the Childs River, nitrate made up significantly more than half of the total nitrogen pool (80%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the channel bed down gradient of Johns Pond and up gradient of the gauge was barely taken up by plants within this surface water system, possibly because the transport time would be relatively short once the water discharged from John Pond. Given the relatively high levels of remaining nitrate in the stream discharge, the possibility for additional uptake by up-gradient freshwater systems might be significant in the Childs River sub-watershed.

From the measured nitrogen load discharged by the Childs River to the upper portion of the East Branch of Eel Pond and the nitrogen load determined from the watershed based land use analysis, it appears that there is moderate nitrogen attenuation of upper watershed derived nitrogen during transport to the Childs River. Based upon lower total nitrogen load (3,835 kg yr^{-1}) discharged from the Childs River at Barrows Road compared to that added by the various land-uses to the associated watershed (5,386 kg yr^{-1}), the integrated attenuation in passage through the stream and up-gradient Ponds and freshwater wetlands prior to discharge to the estuary is 29% (i.e. 29% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the nature of the up-gradient pond/wetland/wooded areas capable of attenuating nitrogen. The directly measured nitrogen load from the Childs River was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI).

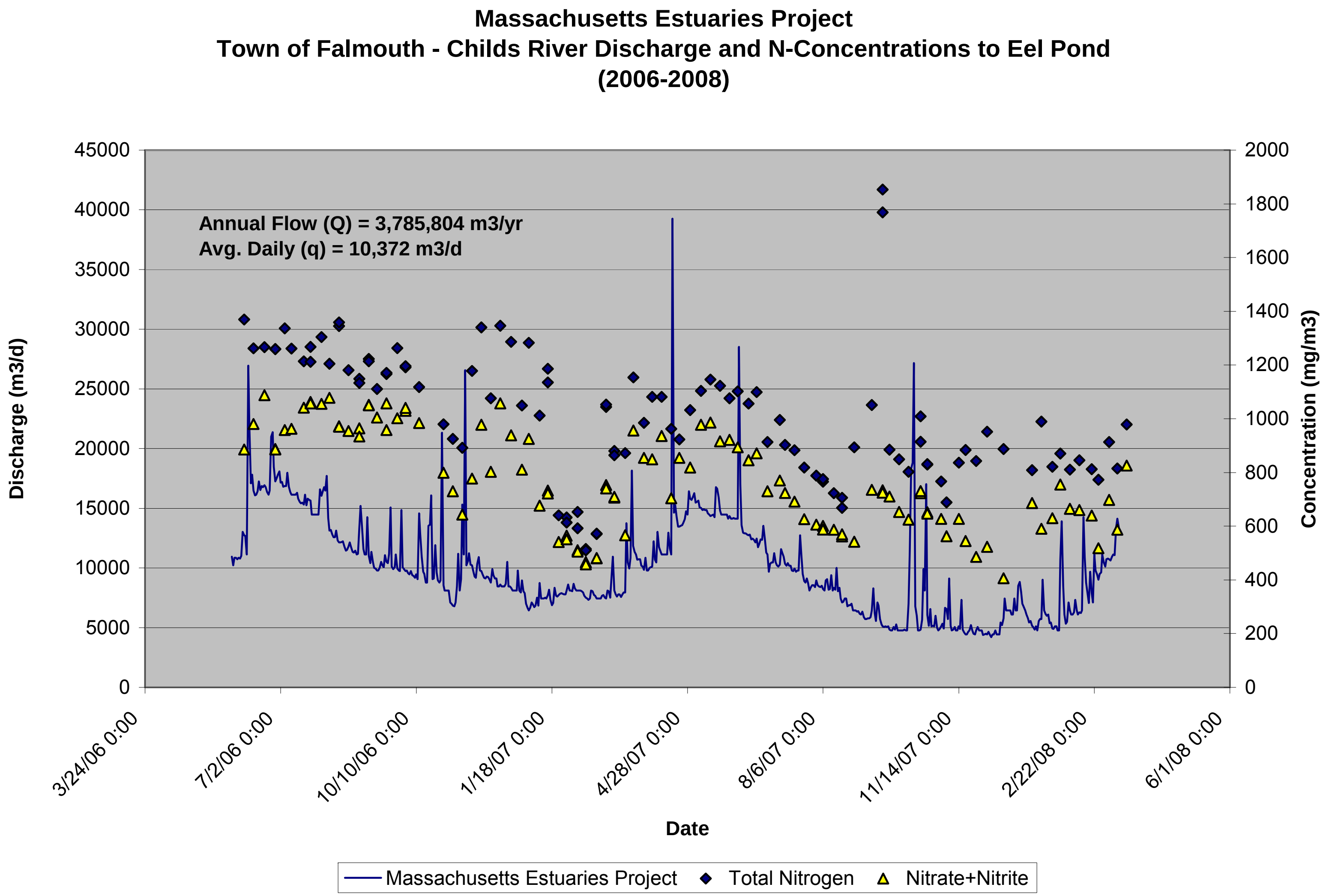


Figure IV-9. Discharge from Childs River (solid blue line), total nitrogen (blue symbols) and NOx (yellow symbols) concentrations for determination of annual volumetric discharge and nitrogen load from the sub-watershed of Childs River discharging to the head of the East Branch of the Eel Pond Sub-embayment to the Waquoit Bay Estuary (Table IV-6).

Table IV-6. Comparison of water flow and nitrogen discharges from the Childs River to the upper estuarine reach of the East Branch of Eel Pond. The "Stream" data are from the MEP stream gauging effort. Watershed data are based on the MEP watershed modeling effort by the USGS.

Stream Discharge Parameter	Discharge Childs River to Eel Pond/Waquoit Bay[b] (MEP)	Data Source
Total Days of Record[a]	365	(1)
Flow Characteristics		
Stream Average Discharge (m3/day)	10372	(1) / (2)
Contributing Area Average Discharge (m3/day)	11492	(3)
Proportion Discharge Stream vs. Contributing Area (%)	9.7%	
Nitrogen Characteristics		
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.2069	(1)
Stream Average Total N Concentration (mg N/L)	0.258	(1)
Nitrate + Nitrite as Percent of Total N (%)	80%	(1)
Total Nitrogen (TN) Average Measured Stream (kg/d)	10.51	(1)
TN Average Contributing Area UN-attenuated Load (kg/d)	14.76	(3)
Attenuation of Nitrogen in Pond/Stream (%)	29%	(4)

[a] from September 1, 2006 to August 31, 2007
[b] Flow and N load to Childs River including John's Pond Contributing Area

(1) MEP develop stream rating curve.
(2) MEP stage and flow data.
(3) Calculated from MEP watershed delineations to John's Pond; the fractional flow path from each sub-watershed which contribute to Childs River; and the annual recharge rate.
(4) As in footnote #3, with the addition of pond and stream conservative attenuation rates.
(5) Calculated based upon the measured TN discharge from the river vs. the unattenuated watershed load.

Table IV-7. Summary of Flow and Nutrient loads from the Childs River discharging to tidally influenced Eel Pond.

Embayment System	Period of Record	Discharge (m^3/year)	Attenuated Load (kg/year)	
			Nox	TN
Childs River (MEP)	September 1, 2006 to August 31, 2007	3785804	3075	3835
Childs River (CCC)		4194580	-	-

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the Benthic Nutrient Flux Task was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters within each major basin area within the Waquoit Bay Embayment System, including the main basin of Waquoit Bay, Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River, Eel Pond and Childs River. 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 above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the estuarine waters of the Waquoit Bay Embayment System predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters from Vineyard Sound. If all of the nitrogen remained within the water column (once it entered), then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. they are 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 (e.g. Vineyard Sound). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with their associated nitrogen "load" become incorporated into the surficial sediments of the bays.

In general the fraction of the phytoplankton population which enters the surficial sediments of a shallow embayment: (1) increases with decreased hydrodynamic flushing, (2) increases in low velocity settings, (3) increases within small enclosed basins (e.g. Hamblin Pond, Jehu Pond, Eel Pond, Childs River, Quashnet River and upper Eel Pond). To some extent, the settling characteristics can be evaluated by observation of the grain-size and organic content of sediments within an estuary.

Once organic particles become incorporated into surface sediments, they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by the MEP Technical Team, 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. Failure to account for this recycled nitrogen generally results in significant errors in determination of threshold nitrogen loadings. 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

Sediment-water column exchange was determined throughout the estuarine reach of the Waquoit Bay Embayment System. All assays were conducted in summer, with the eastern embayments sampled in 2001 and the main basin of Waquoit Bay, Eel Pond and the Child's River in 2006. For the Hamblin Pond/Little River, Jehu Pond/Great River and Quashnet River estuaries, in order to determine the contribution of sediment regeneration to nutrient levels, sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected, during the most sensitive summer interval (July-August), from 16 sites (Figure IV-10) as part of the Mashpee Sewer Commission investigation supporting wastewater facility planning. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core. As part of a separate research investigation, the rate of oxygen uptake was also determined with measurements of sediment bulk density, organic nitrogen, and carbon content. These measurements were made by the MEP Technical Team members in the Coastal Systems Program at SMAST-UMD working with the Town of Mashpee. In addition, within the main basin of Waquoit Bay, Eel Pond and the Childs River (inclusive of the Seapit River connection to the main basin of Waquoit Bay), MEP Technical Team members collected sediment cores at 40 locations (Figure IV-11). The additional sediment cores were collected and incubated in the same manner as for the eastern sub-embayments. The exchange measurements focused on the most sensitive summer interval (July-August), which is the critical period for nitrogen related impairments to water quality and associated estuarine habitats.

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 a small boat. 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. Sampling was distributed throughout each sub-embayment (Figure IV-10 and IV-11) and the results for each site combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

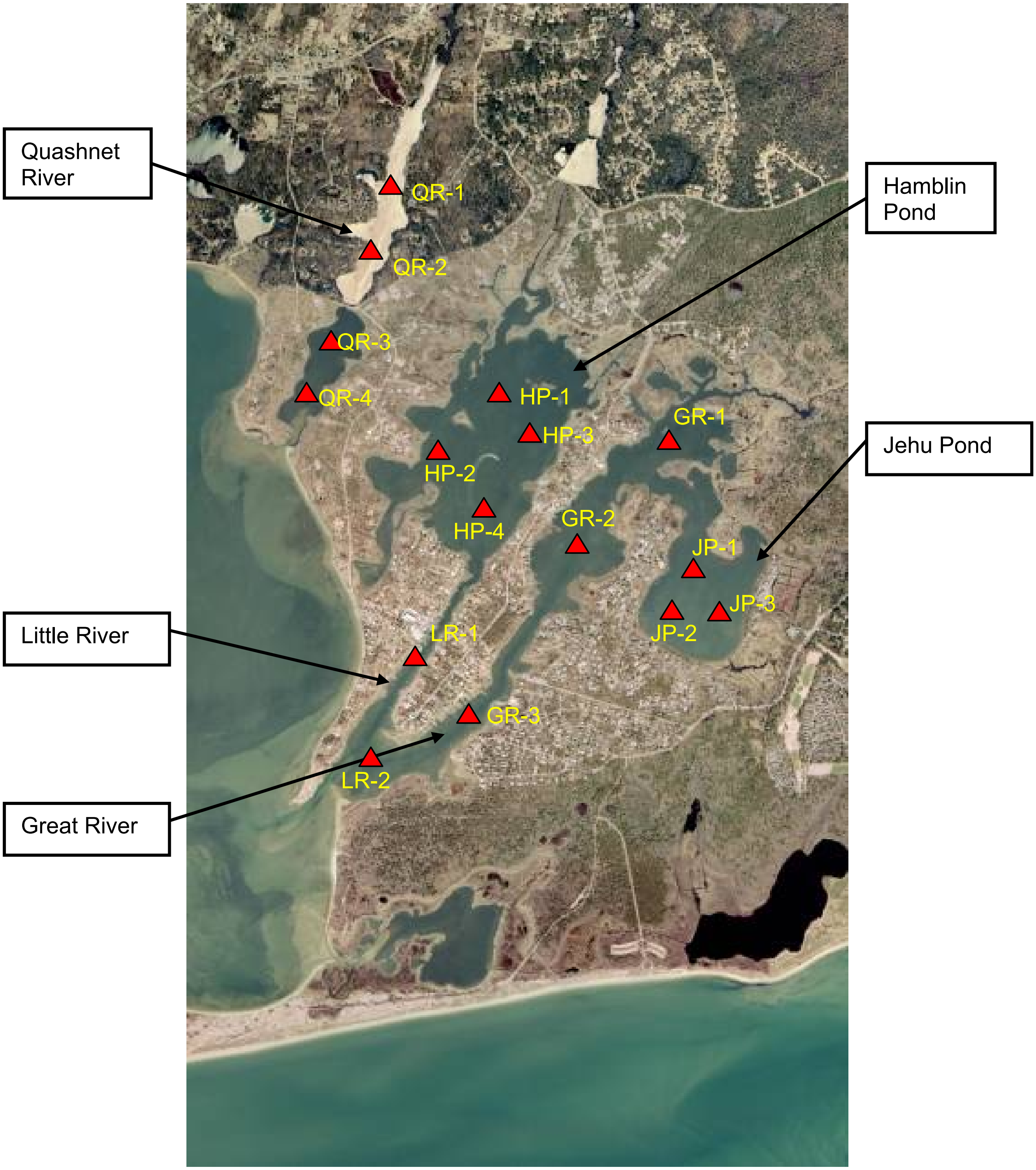


Figure IV-10. Quashnet River, Hamblin Pond/Little River and Jehu Pond/Great River sub-embayments to the Waquoit Bay System, locations (red triangles) of sediment sample collection for determination of nitrogen regeneration rates. Numbers are for reference to Table IV-8.

Figure IV-11. Waquoit (main bay), Eel Pond, and Childs River sub-embayments to the Waquoit Bay System, locations (yellow symbols) of sediment sample collection for determination of nitrogen regeneration rates. Numbers are for reference to Table IV-8.

Sediment-water column exchange follow the methods of Jorgensen (1977), Klump and Martens (1983), and Howes et al. (1995) for nutrients and metabolism. Upon return to the field laboratory (private residence located near shore of Waquoit Bay), 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) assay was conducted within 24 hours and the remaining sample frozen (-20^{o}C) for assay of nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON (D'Elia et al., 1977). Rates were determined from linear regression of analyte concentrations through time.

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

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments Waquoit Bay System

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

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

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

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

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-12).

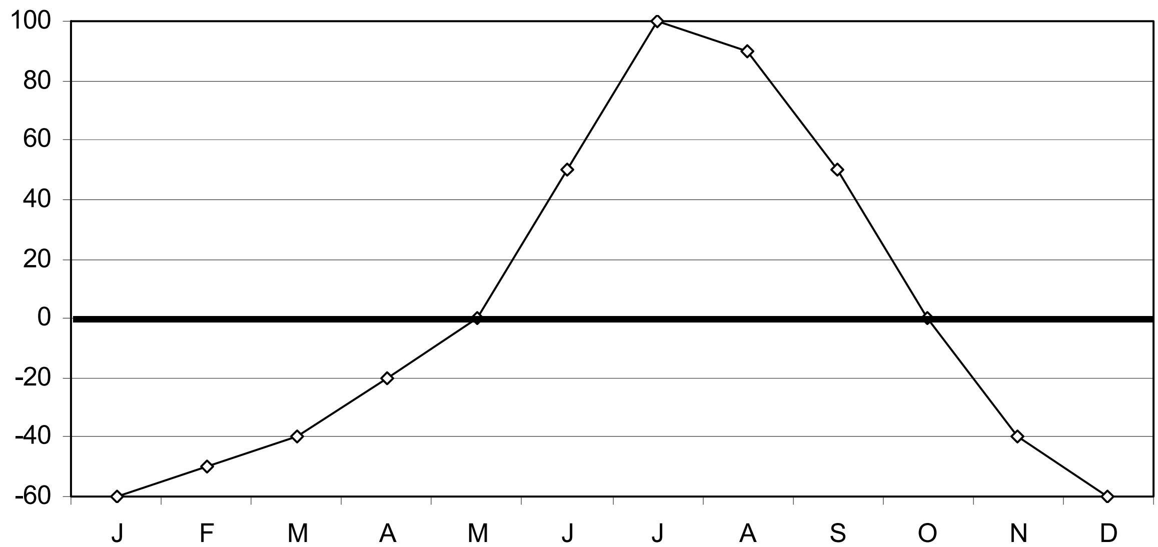


Figure IV-12. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

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

Sediment sampling was conducted throughout the primary component basins (e.g. Waquoit Bay main basin, Eel Pond, Child's River, Quashnet River, Hamblin and Jehu Ponds and Sage Lot Pond) which comprise the Waquoit Bay Embayment System, in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores within each sub-embayment was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

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

Net nitrogen release or uptake from the sediments within the Waquoit Bay Embayment System were comparable to other similar embayments with similar configuration and flushing rates in southeastern Massachusetts. In addition, the spatial pattern of sediment N release was also similar to other systems, with the enclosed basins showing net nitrogen release and the embayment depositional basins with oxidized surficial sediments showing low rates of net nitrogen uptake.

Moderate rates of sediment nitrogen release were observed in the enclosed depositional basins comprised of soft organic rich mud generally with a thin oxidized surface layer. These basins tended to have similar basin morphologies, tidal velocities and sediment characteristics and similar rates of net nitrogen release (Hamblin Pond/Little River, 9-28 mg N $m^{-2}d^{-1}$; Jehu Pond Great River, 52-94 mg N $m^{-2}d^{-1}$; and Quashnet River, 59-76 mg N $m^{-2}d^{-1}$). These basins are similar to the upper enclosed basins of Bass River (Follins Pond, 46 mg N $m^{-2}d^{-1}$; Kelleys Bay, 75.1 mg N m^{-2}d-1 ; and Grand Cove, 80.9 mg N $m^{-2}d^{-1}$) and other sub-embayments on Cape Cod, for example the depositional main basin of East Bay (Centerville River Estuary) and lower basin Rock Harbor (Orleans/Eastham) support benthic regeneration rates of 59.1 mg N $m^{-2}d^{-1}$ and 80.8 mg N $m^{-2}d^{-1}$, respectively. Additionally, the analogous drowned kettle basins within the Pleasant Bay Estuary, Meetinghouse Pond (79.5 mg N $m^{-2}d^{-1}$ mg N $m^{-2}d^{-1}$), Areys Pond (107.3 mg N $m^{-2}d^{-1}$), Lonnies Pond (22.7 mg N $m^{-2}d^{-1}$), Quanset Pond (98.0 mg N $m^{-2}d^{-1}$), and Paw Wah Pond (120.7 mg N $m^{-2}d^{-1}$) also have similar basins and net rates of nitrogen release. The observed sediment release rates within Quashnet River is most notably similar to the Mashpee River in adjacent Popponessett Bay, which has comparable hydrologic and physical characteristics (Quashnet River mean=67 mg N $m^{-2}d^{-1}$ and Mashpee River mean=72 mg N $m^{-2}d^{-1}$). In contrast, the more directly connected open water basins with generally unconsolidated mud (soft organic enriched mud) with thin oxidized surface layers and little bioturbation showed moderate rates of net nitrogen uptake (Waquoit main basin, -16 to -32 $m^{-2}d^{-1}$ Eel River/Pond, -27 to -29 $m^{-2}d^{-1}$; and Child's River, -45 mg N $m^{-2}d^{-1}$). These rates were also similar to other nutrient enriched depositional basins with organic enriched soft sediments, such as Swan Pond (-8 mg N $m^{-2}d^{-1}$), Seine Pond, -16.9 mg N $m^{-2}d^{-1}$, Scudder Bay (-13.2 mg N $m^{-2}d^{-1}$), and the large lower basin of the Three Bays Estuary, Cotuit Bay (-29.1 mg m^{-2} d^{-1}).

Net nitrogen release rates for use in the water quality modeling effort for the main basins of the Waquoit Bay Embayment System (Section VI) are presented in Table IV-8. There was a clear spatial pattern of sediment nitrogen flux, with moderate net uptake of nitrogen in the main depositional basins and net release within the enclosed brackish water basin (Quashnet River) and terminal basins of Hamblin and Jehu Ponds. The sediments within the Waquoit Bay Embayment System showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and are consistent with the level of nitrogen loading to this system and its rates of tidal flushing.

Table IV-8. Rates of net nitrogen return from sediments to the overlying waters of the component basins comprising of the Bass River Estuarine System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Section VI). Measurements represent July - August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			Station I.D. *
	Mean	S.E.	# sites	#
Waquoit Bay Embayment System - Eastern Sub-embayments				
Hamblin Pond	9.3	30.1	4	HP1-4
Little River	27.8	7.1	2	LR 1-2
Jehu Pond	51.9	15.9	3	JP 1-3
Great River	93.7	36.3	3	GR 1-3
Quashnet River (upper)	75.9	25.9	2	QR 1,2
Quashnet River (lower)	58.8	16.4	2	QR 3,4
Sage Lot Pond	-20.32	4.39	1	29
Waquoit Bay Embayment System - Main Basin Waquoit Bay				WAQ-#
Upper Basin	-31.9	4.7	6	21-24,39,40
Lower Basin	-16.4	6.4	12	25-27,30-38
Waquoit Bay Embayment System - Western Sub-embayments				WAQ-#
Eel River	-29.2	9.5	5	1,2,4,5,6
Eel Pond	-27.1	6.5	3	7,8,16
Child's River	-45.2	18.2	5	9-13
Seapit River	64.3	33.9	6	14,15,17-20

* Station numbers refer to Figures IV-11 and 12.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

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

In general, water quality studies of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. For example, the spread of pollutants may be analyzed from tidal current information developed by the numerical models.

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

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

Figure V-1. 1994 aerial photograph of the Waquoit Bay system. Secondary inlet to Eel Pond did not exist during the MEP modeling of the system.

This hydrodynamic study 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 Waquoit Bay was performed to determine the present variation of embayment and channel depths throughout the system. In addition to bathymetry, tides were recorded at six locations within the Waquoit Bay system for 29 days, a complete lunar month. These tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of the Waquoit Bay system was developed in the second portion of this analysis. Using the bathymetry survey data, a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data from offshore of the entrance to Eel Pond, in Vineyard Sound, were used to define the open boundary conditions that drive the circulation of the model at the system inlets, Waquoit Bay and Eel Pond. Data from the six gaging stations within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the real, physical system.

V.2. FIELD DATA COLLECTION AND ANALYSIS

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

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

System geometry is defined by the shoreline of the system, including all coves, creeks, and marshes, as well as accompanying depth (or bathymetric) information. The three-dimensional surface of the estuary is mapped as accurately as possible, since the resulting hydrodynamic behavior is strongly dependent upon features such as channel widths and depths, sills, marsh elevations, and inter-tidal flats. Hence, this study included an effort to collect bathymetric information in the field where the coverage of historical bathymetry data lacked accuracy and/or detail necessary for evaluation of tidal hydrodynamics. Detailed bathymetric surveys of Eel Pond, Childs River, Seapit River, Quashnet River, Great River and the inlets were conducted.

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

V.2.1 Bathymetry

Bathymetry, or depth, of Waquoit Bay System was measured during field surveys in January 2002. The surveys were completed using a small vessel equipped with a precision fathometer interfaced to a differential GPS receiver. The fathometer has a depth resolution of approximately 0.1 foot and the differential GPS provides x-y position measurements accurate to approximately 1-3 feet. Digital data output from both the echo sounder and GPS were logged to a laptop computer. Survey transects within the system were densest in the vicinity of the inlets and channel constrictions, were the greatest variability in bottom bathymetry was expected. Bathymetry in the inlets is important from the standpoint that they have the most influence on tidal circulation in and out of the estuary.

GPS positions and echo sounder measurements were merged to produce data sets consisting of water depth as a function of x-y horizontal position (in Massachusetts Mainland State Plane, 1983). The data were combined with water surface elevations to obtain the vertical elevation of the bottom (z) relative to the NGVD 1929 vertical datum (NGVD29). The resulting xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The final processed bathymetric data from the survey are presented in Figure V-3. The bathymetry collected by Applied Coastal was supplemented with data from NOAA.

Figure V-2. Waquoit Bay system with tide gauge locations labeled as W1-W7.

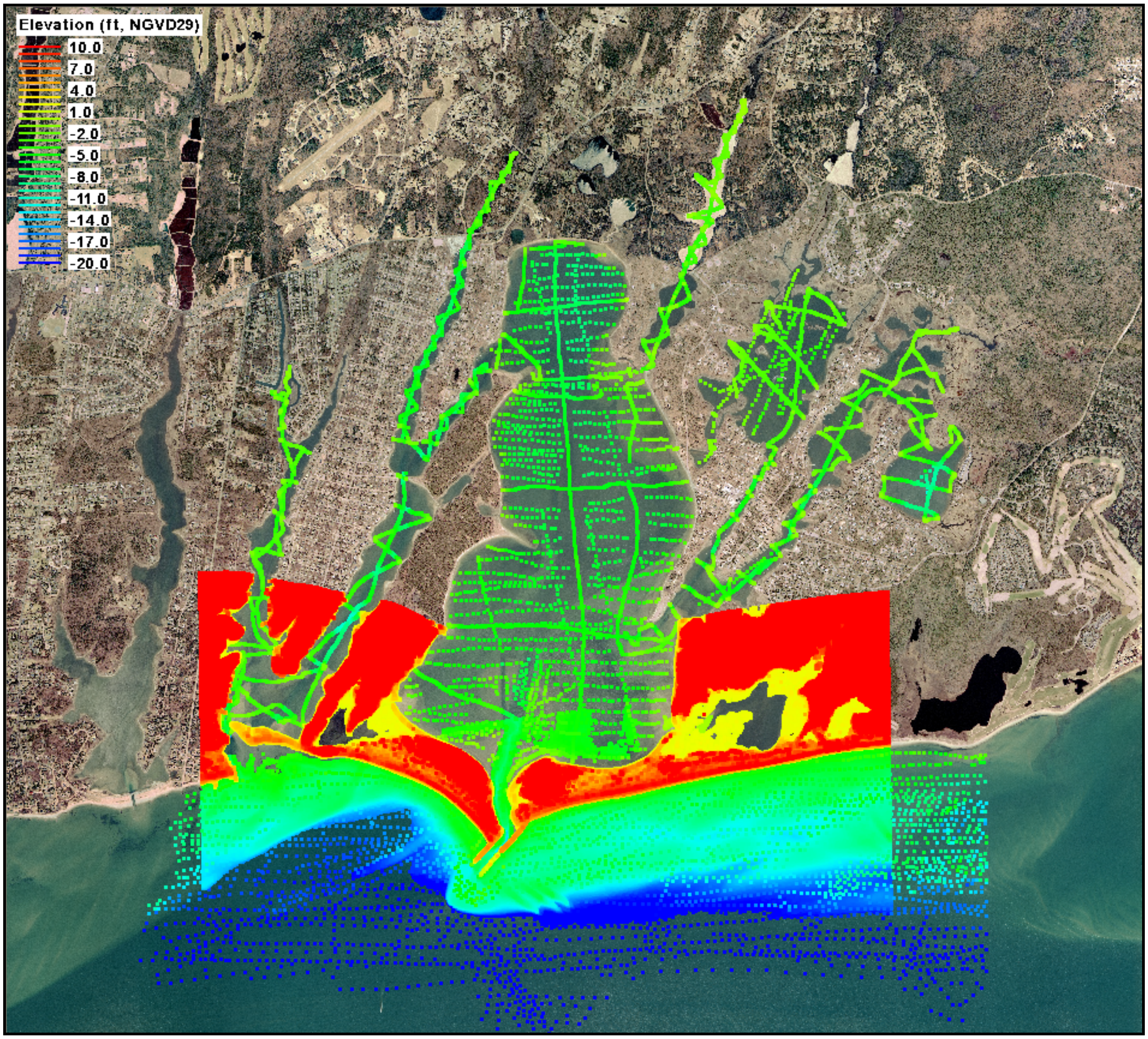


Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model, elevation is relative to NGVD29.

V.2.2 Water Elevation Measurements and Analysis

Changes in water surface elevation were measured using internal recording tide gauges. These tide gauges were installed on fixed platforms (such as pier pilings) to record changes in water pressure over time. Variations in the water surface can be due to tides, wind set-up, or other low frequency oscillations of the sea surface. The tide gauges were installed at 7 locations in the Waquoit Bay region (Figure V-2) on January 18, 2002 and recovered on February 19, 2002. Data records span at least 29 days to yield an adequate time period for resolving the primary tidal constituents.

The tide gauges used for the study consisted of Brancker TG-205, Brancker XR-420 TG, and Global Water WL-15 instruments. Data were set for 10-minute intervals, with each observation resulting from an average of 60 1-second pressure measurements on 10-minute intervals. Each of these instruments use strain gauge transducers to sense variations in pressure, with resolution on the order of 1 cm (0.39 inches) head of water. Each gauge was calibrated prior to installation to assure accuracy.

Once the data were downloaded from each instrument, the water pressure readings were corrected for variations in atmospheric pressure. Hourly atmospheric readings were recorded by the Global Water WL-15 gauge, interpolated to 10-minute intervals, and subtracted from the pressure readings, resulting in water pressure above the instrument. Further, a (constant) water density value of 1025 kg/m^3 was applied to the readings to convert from pressure units (psi) to head units (for example, feet of water above the tide gauge). Several of the sensors were surveyed into local benchmarks to provide vertical rectification of the water level; these survey values were used to adjust the water surface to a known vertical datum. The result from each gauge is a time series representing the variations in water surface elevation relative to NGVD29. Figures V-4 and V-5 present the water levels at each gauge location.

Figure V-4 shows the tidal elevation for the period January 18 through February 19, 2002 at four locations: offshore Menauhant Beach in Vineyard Sound (Location W1), Eel Pond (Location W2), Waquoit Bay (Location W3), and Childs River (Location W4). Tidal elevations are shown for the next three locations in Figure V-5: Moonakis/Quashnet River (Location W5), Hamblin Pond (Locations W6), and Great River (Locations W7). The curves have a predominant 12.42-hour variation around the lunar semi-diurnal (twice-a-day), or M_2, tidal constituent. Modulation of the lunar and solar tides, results in the spring-neap fortnightly cycle, typically evidenced by a gradual increase and decrease in tide range. Water elevations in the Waquoit Bay System are strongly influenced by wind set-up resulting in a lowering of the water surface, clearly seen on February 2. The spring-neap cycle variation is masked by sudden changes in water surface elevation as a result of wind events. The neap (or minimum) tide range was approximately 1.8 feet, occurring January 20. The spring (maximum) tide range was approximately 3 feet, and occurred on January 31.

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

The loss of amplitude together with increasing phase delay with increasing distance from the inlet is described as tidal attenuation. Tidal attenuation can be a useful indicator of flushing efficiency in an estuary. Attenuation of the tidal signal is caused by the geomorphology of the near-shore region, areas with channel restrictions (e.g. bridge abutments, culverts, shoals, etc.), and also the depth of an estuary are the primary factors which influence tidal damping in estuaries. A visual comparison of the six stations throughout the Waquoit Bay estuary system as well as the one Vineyard Sound station is shown in Figure V-6. The figure demonstrates clearly the reduction in the tidal efficiency as the tide propagates into and through Hamblin Pond and Great River.

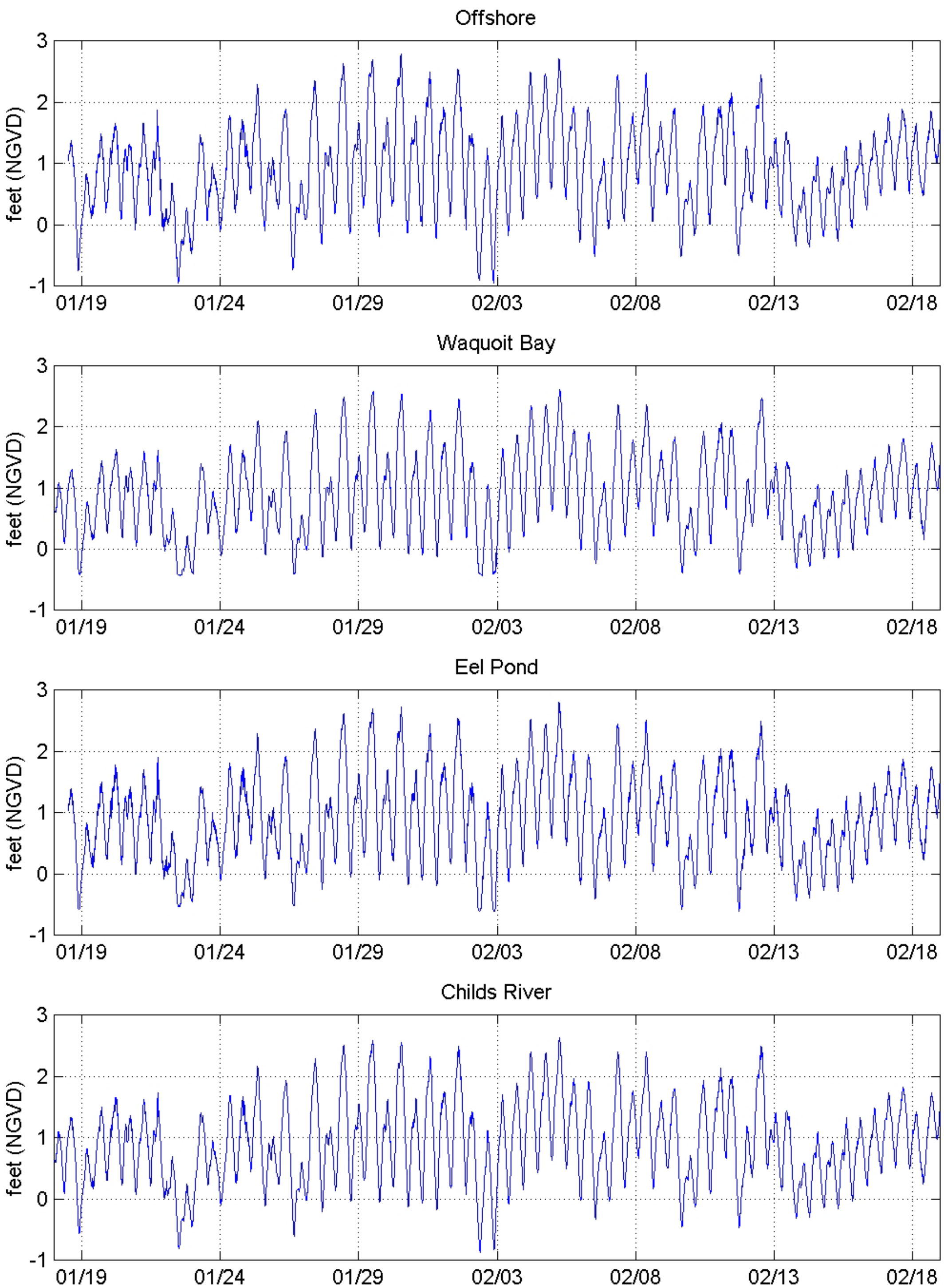


Figure V-4. Tidal elevation observations for offshore Menauhant Beach (location W1), Waquoit Bay (location W3), Eel Pond (location W2), Childs River (location W4).

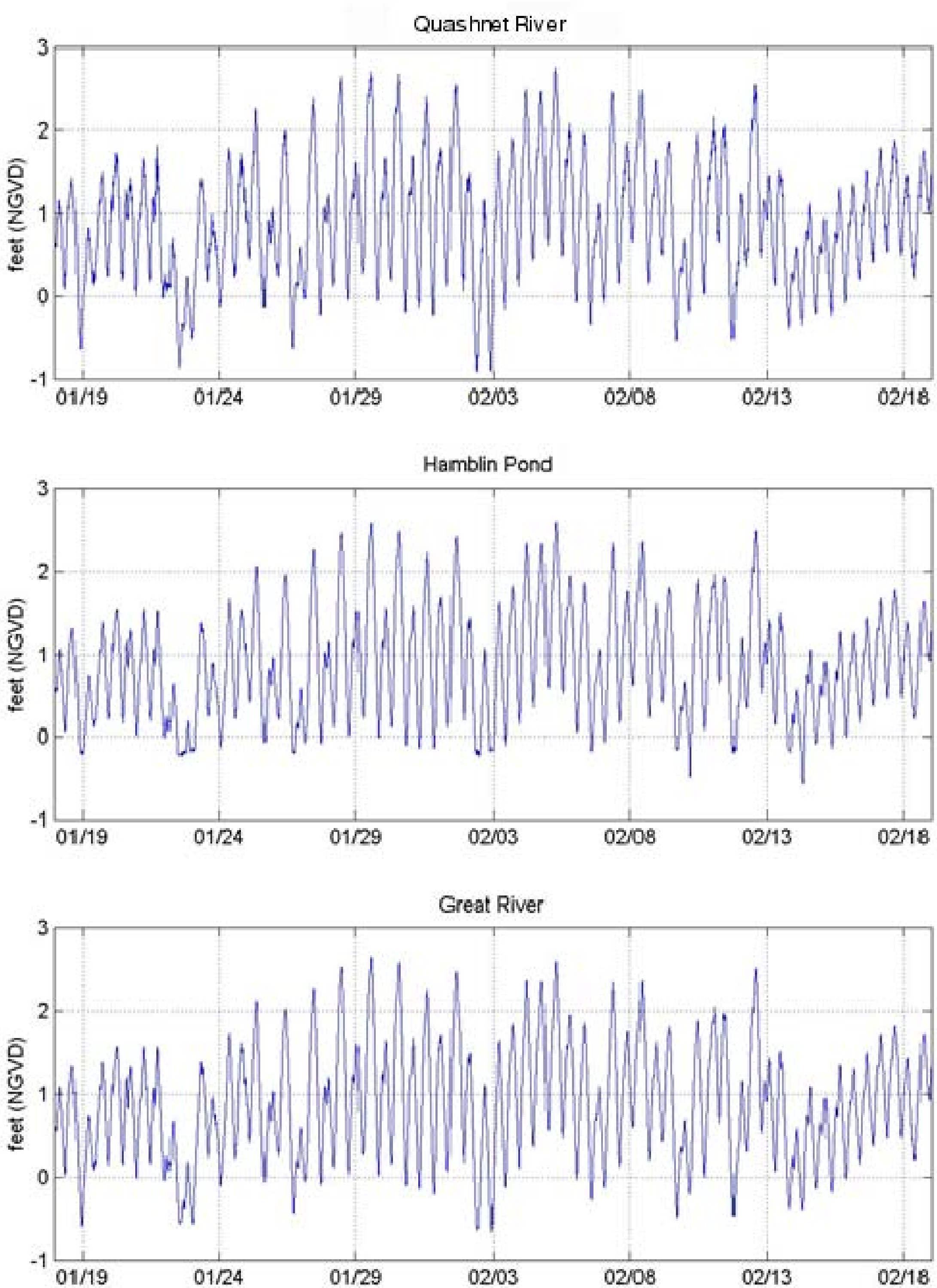


Figure V-5. Tidal elevation observations for Quashnet River (location W5), Hamblin Pond (location W6), and Great River (location W7).

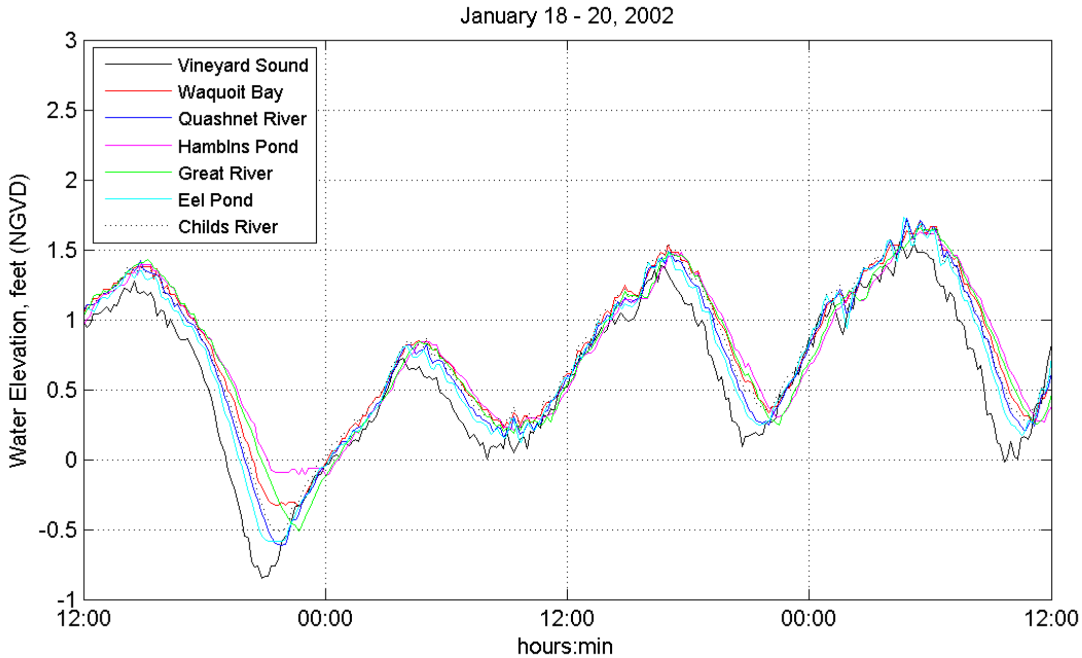


Figure V-6. Comparison of water surface elevation observations for Vineyard Sound (offshore), and six locations within the Waquoit Bay system. Damping effects are seen as a decrease in the tidal amplitude, as well as a lag in the time of high and low tides from Vineyard Sound.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 29-day records. These datums are presented in Table V-1. The Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW. The tides in Vineyard Sound are semi-diurnal, meaning that there are typically two tide cycles in a day. There is usually a small variation in the level of the two daily tides. This variation can be seen in the differences between the MHHW and MHW, as well as the MLLW and MLW levels

For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data was available; however, these datums still provide a useful comparison of tidal dynamics within the system. From the computed datums, it further apparent that there is little tide damping throughout the system.

Table V-1. Tide datums computed from records collected in the Waquoit Bay system from January 18, 2002 to February 19, 2002. Datum elevations are given relative to NGVD29.							
Tide Datum	Vineyard Sound (W1)	Eel Pond (W2)	Waquoit Bay (W3)	Childs River (W4)	Moonakis/ Quashnet River (W5)	Hamblin Pond (W6)	Great River (W7)
Maximum Tide	2.78	2.82	2.69	2.69	2.75	2.69	2.68
MHHW	1.98	2.01	1.98	1.98	1.99	1.98	1.95
MHW	1.70	1.72	1.70	1.69	1.69	1.69	1.68
MTL	0.85	0.89	0.93	0.89	0.86	0.94	0.88
MLW	0.00	0.07	0.16	0.10	0.03	0.19	0.08
MLLW	-0.18	-0.09	0.01	-0.07	-0.14	0.05	-0.07
Minimum Tide	-0.96	-0.56	-0.36	-0.82	-0.91	-0.46	-0.62

Harmonic analyses were 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 amplitudes and phase of 23 known tidal constituents result from this procedure. Table V-2 presents the amplitudes of the eight largest tidal constituents. The M_2, or the familiar twice-a-day lunar semi-diurnal, tide is the strongest contributor to the signal with an amplitude of 0.68 feet at the offshore gauge. The range of the M_2 tide is twice the amplitude, or 1.36 feet. The diurnal tides, K_1 and O_1, possess amplitudes of approximately 0.25 feet. The N_2 (12.66-hour period) semi-diurnal tide, also contributes significantly to the total tide signal with an amplitude of 0.22 feet. 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 for the M_6), results from frictional attenuation of the M_2 tide in shallow water. The M_4 is approximately 20% of the amplitude of the M_2 in the offshore gauge (about 0.16 feet). The M_6 amplitude is relatively small throughout the system (less than 0.06 feet). The M_{sf} is a lunarsolar fortnightly constituent with a period of approximately 14 days, and is the result of the periodic conjunction of the sun and moon. The observed astronomical tide is therefore the sum of several individual tidal constituents, with a particular amplitude and frequency.

Table V-2. Tidal Constituents, Waquoit Bay System January-February 2002								
	Amplitude (feet)							
	M2	M4	M6	S2	N2	K1	O1	Msf
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Offshore (W1)	0.68	0.16	0.06	0.06	0.24	0.25	0.23	0.89
Eel Pond (W2)	0.65	0.12	0.05	0.05	0.22	0.25	0.23	0.80
Waquoit Bay (W3)	0.64	0.10	0.04	0.05	0.22	0.25	0.23	0.80
Childs River (W4)	0.67	0.10	0.06	0.05	0.23	0.27	0.24	0.86
Quashnet River (W5)	0.65	0.09	0.05	0.05	0.22	0.25	0.23	0.81
Hamblin Pond (W6)	0.63	0.07	0.05	0.05	0.21	0.25	0.23	0.78
Great River (W7)	0.67	0.13	0.06	0.06	0.23	0.27	0.23	0.89

Table V-2 also shows how the constituents vary as the tide propagates into the estuaries. The most significant reduction in the M_2 amplitude occurs between the Vineyard Sound (offshore) gauge and the upper reaches of Hamblin Pond. Usually, a portion of the energy lost from the M_2 tide is transferred to higher harmonics, and is observed as an increase in the amplitude of the M_4 and M_6 constituents over the length of the estuary. However, in the Waquoit Bay system M_2, M_4 and M_6 are all clearly smaller than the amplitudes at the inlet. This is likely because the tidal attenuation through the two inlet channels is much stronger than the damping from frictional drag through tidal channels.

Table V-3 presents the phase delay of the M_2 tide at all tide gauge locations compared to the offshore gauge in Vineyard Sound. Phase delay is another indication of tidal damping, and results with a later high tide at inland locations (Figure V-6). The greater the frictional effects, the longer the delay between locations. The delay in Eel Pond (23.31 minutes) is the smallest, as a result of its proximity to the offshore gauge location. In general, the delays increase with increasing distance from the offshore gauge. However, in the Waquoit Bay system M2, M4 and M6 are all clearly smaller than offshore in Nantucket Sound. This is because the tidal energy loss of the M2 observed between the offshore and bay gauges occurs mostly at the inlets, and not as is propagates across the open water reaches of the Bay. The attenuation at the inlets also reduce the amplitude of the M4, M6, S2, and N2 constituents by varying degrees.

Table V-3. M_2 Tidal Attenuation, Waquoit Bay, January-February 2002 (Delay in minutes relative to Vineyard Sound)

Location	Delay (minutes)
Offshore (Vineyard Sound)	--
Waquoit Bay	48.01
Eel Pond	23.31
Childs River	34.43
Quashnet River	35.29
Hamblin Pond	74.99
Great River	66.54

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. Vineyard Sound is a relatively shallow semi-enclosed basin, therefore the water surface responds readily to wind-forcing. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large. This analysis calculated the energy (or variance) of the original water elevation time series, and compared these energy values to that of the purely tidal signal (re-created by summing the contributions from the 23 known harmonic constituents). Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary. The results of this analysis for the Waquoit Bay system are presented in Table V-4.

Table V-4. Percentages of Tidal versus Non-Tidal Energy, Waquoit, 2002				
	Total Variance ($ft^2 \cdot sec$)	Total (%)	Tidal (%)	Non-tidal (%)
Offshore	0.51	100	72.3	27.7
Waquoit Bay	0.45	100	70.7	29.3
Eel Pond	0.50	100	71.3	28.7
Childs River	0.46	100	70.5	29.5
Quashnet River	0.50	100	70.9	29.1
Hamblin Pond	0.42	100	71.3	28.7
Great River	0.46	100	70.8	29.2

The variability analysis shows that less than three-quarters of the changes in water surface elevation in Vineyard Sound and the Waquoit Bay system were due to tidal processes. More than one-quarter of the energy in Vineyard Sound water elevations was the result of non-tidal processes. The percentage of non-tidal energy increases and the percentage of tidal energy decreases as the residual signal propagates into the system. As mentioned previously, this is in part due to tidal damping through the inlets. However, local effects of wind blowing across each pond or river surface will increase the energy of non-tidal processes. These results indicate that hydrodynamic circulation in each of the embayments is dependent primarily upon tidal processes, with a secondary, but significant contribution from wind forces.

V.3. HYDRODYNAMIC MODELING

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

V.3.1 Model Theory

The analysis of the Waquoit Bay utilized a numerical computer model to evaluate tidal and river hydraulics. 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. Finite element models are well-suited to modeling estuarine and riverine areas with complex shoreline and bathymetric contours, and also allow for greater density of computational elements to be applied in areas of interest in the model domain. RMA-2 is widely accepted and tested for analyses of estuaries or rivers.

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. Graphic pre- and post-processing routines are supplied by Aquaveo through a software package called the Surface-water Modeling System or SMS. SMS is a front- and back-end software package that allows the user to easily modify model parameters (such as geometry, element coefficients, and boundary conditions), as well as view the model results and download specific data types. While the RMA model is essentially used without cost or constraint, the SMS software package requires site licensing for use.

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

The extent of the finite element grid was generated using digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the two entrances to Waquoit Bay System based on the tide gauge data collected in Vineyard Sound. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several model calibration simulations for each system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid Generation

The grid generation process for the model was assisted through the use of the SMS package. The digital shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary with 4190 elements and 11818 nodes. All regions in the system were represented by two-dimensional (depth-averaged) elements. The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties within the estuary. Fine resolution was required to simulate the channel constrictions that significantly impact the estuarine hydrodynamics. The completed grid is made up of quadrilateral and triangular two-dimensional elements. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the recent field surveys and the historic survey data. In the model grid, a typical marsh plain elevations of approximately 1.5 ft (NGVD 29) were used, based on spot surveys across the marsh plain. The model marsh topography was varied to provide a monotonically sloping surface, in order to enhance the stability of the hydrodynamic model. The final interpolated grid bathymetry is shown in Figure V-7. The model computed water elevation and velocity at each node in the model domain.

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

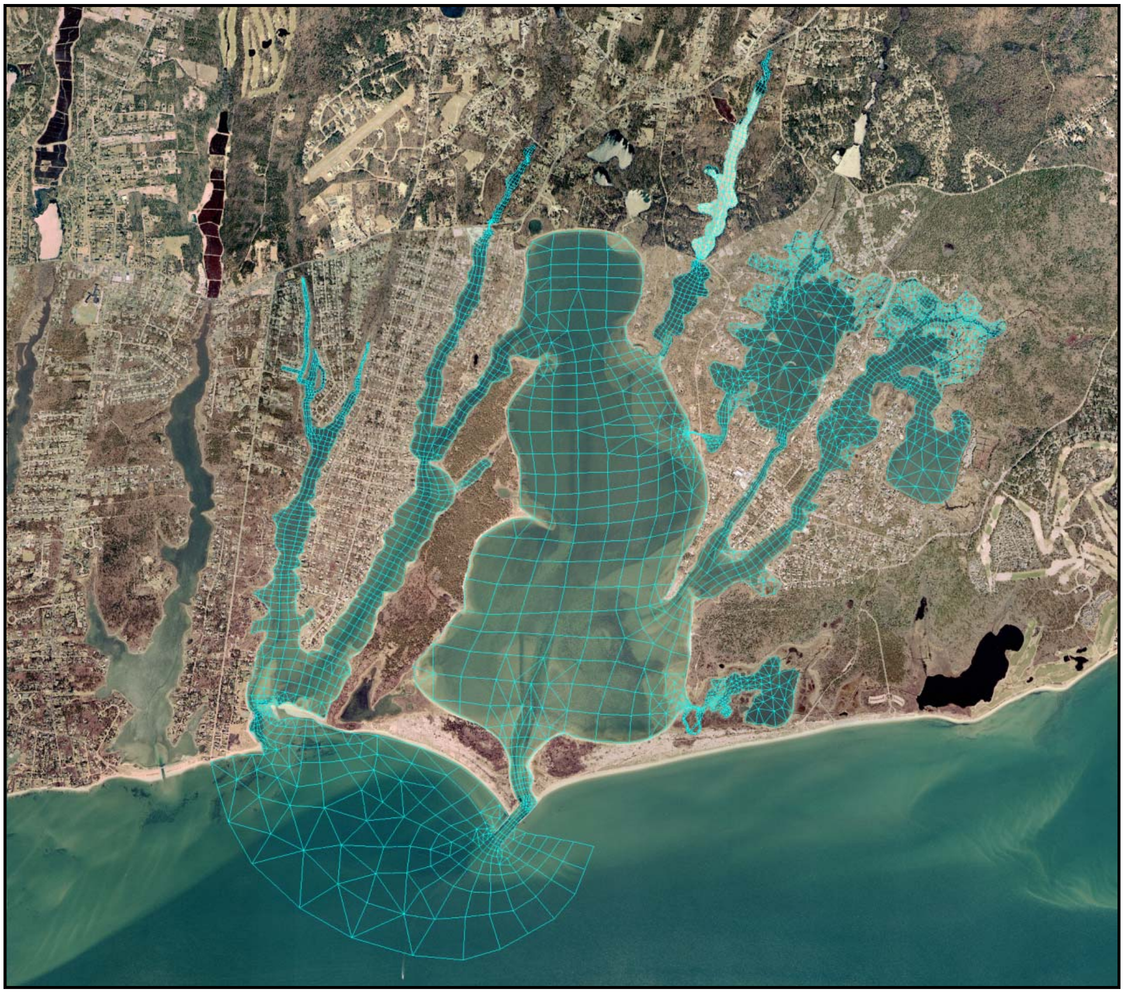


Figure V-7. Plot of hydrodynamic model grid mesh for the Waquoit Bay system.

V.3.2.2 Boundary Condition Specification

Two types of boundary conditions were employed for the RMA-2 model of the Waquoit Bay system: 1) "slip" boundaries, and 2) tidal elevation boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. Tidal boundary conditions were specified at the inlets to Waquoit Bay and Eel Pond. TDR measurements provided the required data. The rise and fall of the tide in Vineyard Sound is the primary driving force for estuarine circulation in this system. For the boundaries a dynamic (time-varying) water surface elevation condition was specified every model time step (10 minutes) to represent the tidal forcing.

V.3.2.3 Calibration

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

Calibration of the hydrodynamic model requires a close match between the modeled and measured tides in each of the sub-embayments where tides were measured (i.e., from the TDR deployments). Initially, the model was calibrated to obtain visual agreement between modeled and measured tides. Once visual agreement was achieved, an approximate seven-day period (14 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section V.3.2. The seven-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents

The calibration was performed for a five-day period beginning January 27, 2002 at 1020 EDT. This representative time period included the spring tide range of conditions, where the tide range and tidal currents are greatest.

The calibrated model was used to analyze existing detailed flow patterns and compute residence times. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire five-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.3.2.3.1 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 0.075 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 the smooth sandy channels found in Eel Pond, versus the rock lined channel in the inlet to Hamblin Pond, 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. The extents of each material type are shown in Figure V-8.

Table V-5. Manning's Roughness coefficients used in simulations of modeled embayments. These embayment delineations correspond to the material type areas shown in Figure V-8.

System Embayment	Bottom Friction
Waquoit Bay	0.027
Eel Pond	0.027
Quashnet River	0.026
Seapit River	0.027
Marsh Plain in Hamlin Pond	0.075
Hamblin Pond	0.035
Great River	0.035
Child's River	0.026
Bridge	0.050
Rock lined channel	0.040
Marsh Plain in Great River	0.075
Offshore Eel Pond	0.025
Offshore Waquoit Bay	0.025
Sage Lot Pond	0.028

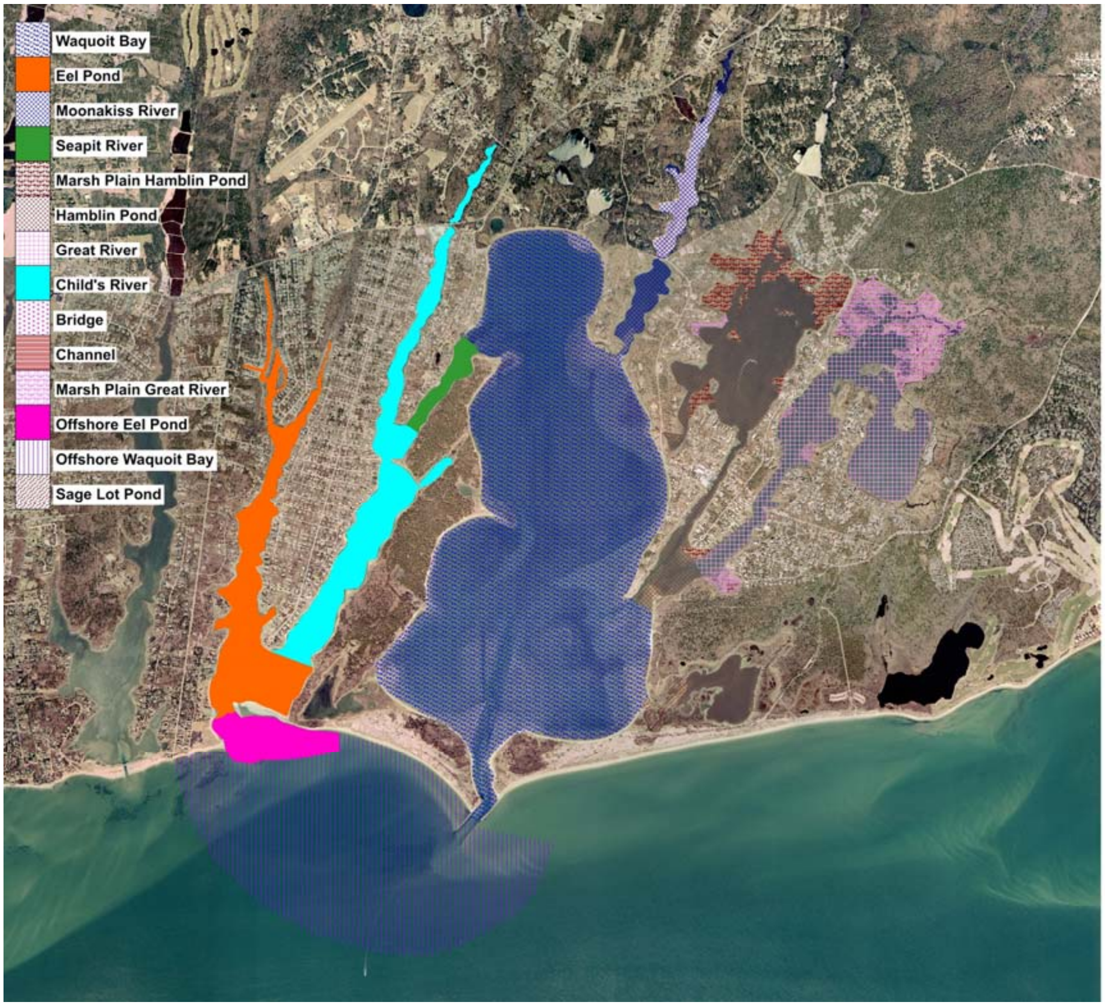


Figure V-8. Hydrodynamic model grid material properties. Color patterns designate the different model material types used to vary model calibration parameters and compute flushing rates.

V.3.2.3.2 Turbulent Exchange Coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 20 and 110 lb-sec/ft^2.

V.3.2.3.3 Marsh Porosity Processes

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

V.3.2.3.4 Comparison of Modeled Tides and Measured Tide Data

A best-fit of model predictions for the first TDR deployment was achieved using the aforementioned values for friction and turbulent exchange. Figures V-9 through V-14 illustrate the seven-day calibration simulation, for Eel Pond, Childs River, Waquoit Bay, Quashnet River, Hamblin Pond, and Great River. 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 modeled systems. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1, M_2, M_4, and M_6. Measured tidal constituent heights (H) and time lags (ϕ_{lag}) shown in Table V-6 for the calibration period differ from those in Table V-2 because constituents were computed for only the seven-day section of the 29-days represented in Table V-2. Table V-6 compares tidal constituent height and phase for modeled and measured tides at the TDR locations.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.03 ft in Quashnet River, which is of the same order of the accuracy of the tide gauges (0.032 ft). Time lag errors were typically less than the time increment resolved by the model (0.10 hours or 10 minutes), indicating good agreement between the model and data. Quashnet River had the largest time lag errors, the largest being approximately 24 minutes. The increased lag times for Quashnet River are likely attributable to deficiency in bathymetric data in Quashnet River.

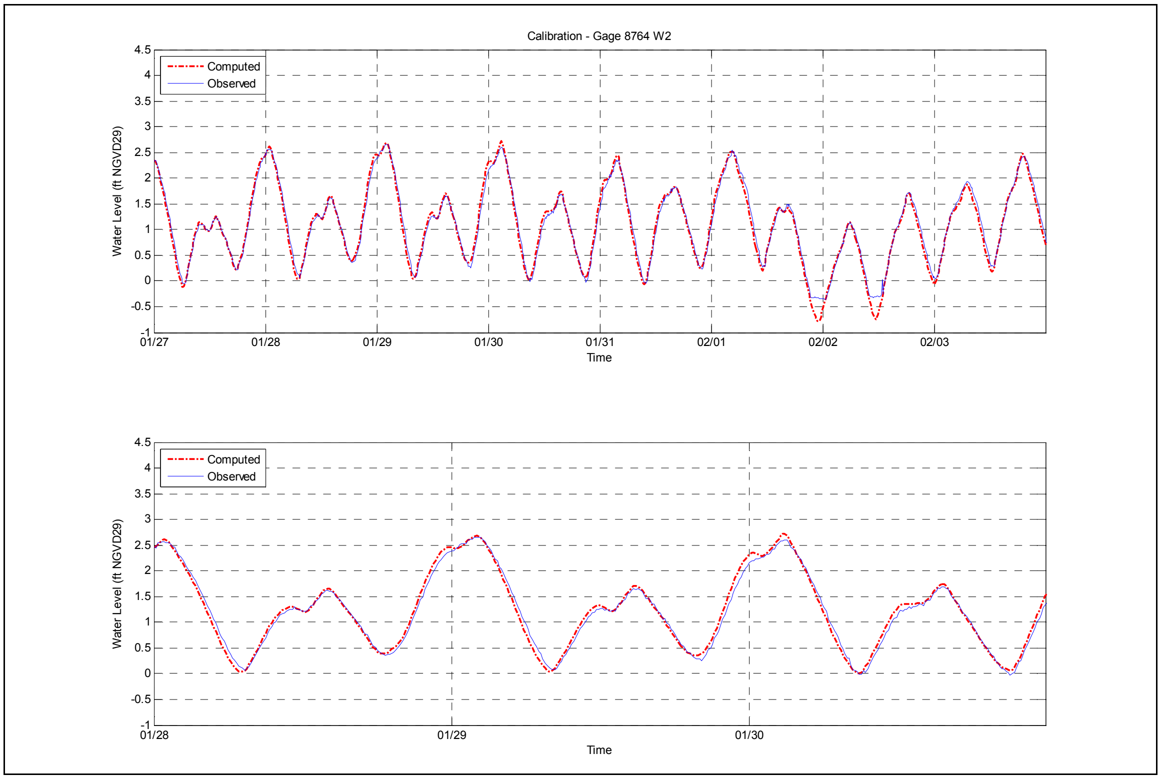


Figure V-9. Comparison of model output and measured tides for the TDR location in Eel Pond.

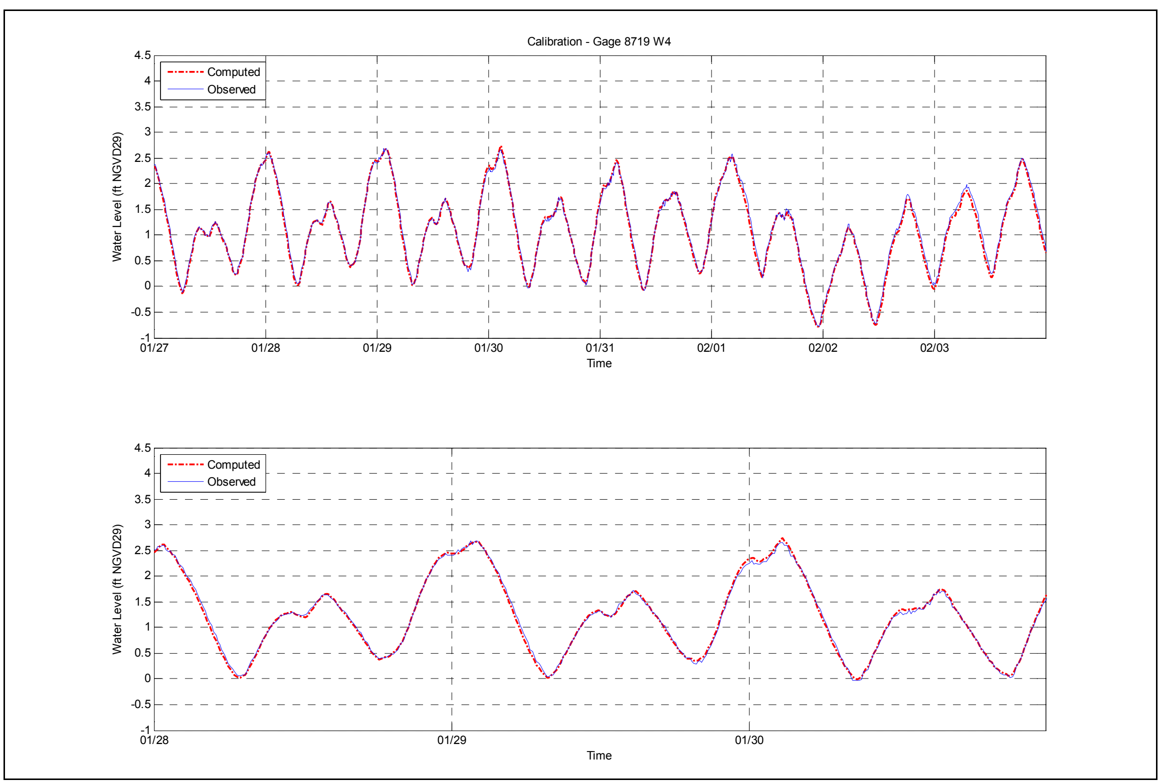


Figure V-10. Comparison of model output and measured tides for the TDR location in Childs River.

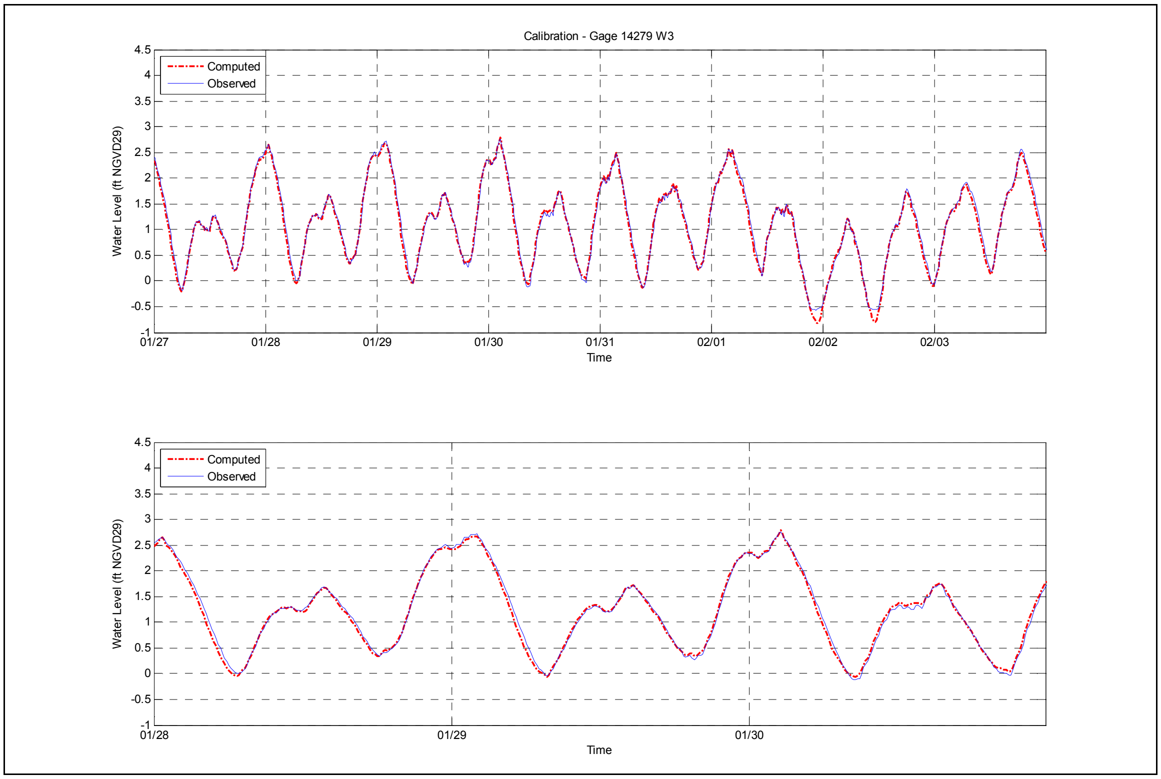


Figure V-11. Comparison of model output and measured tides for the TDR location in Waquoit Bay.

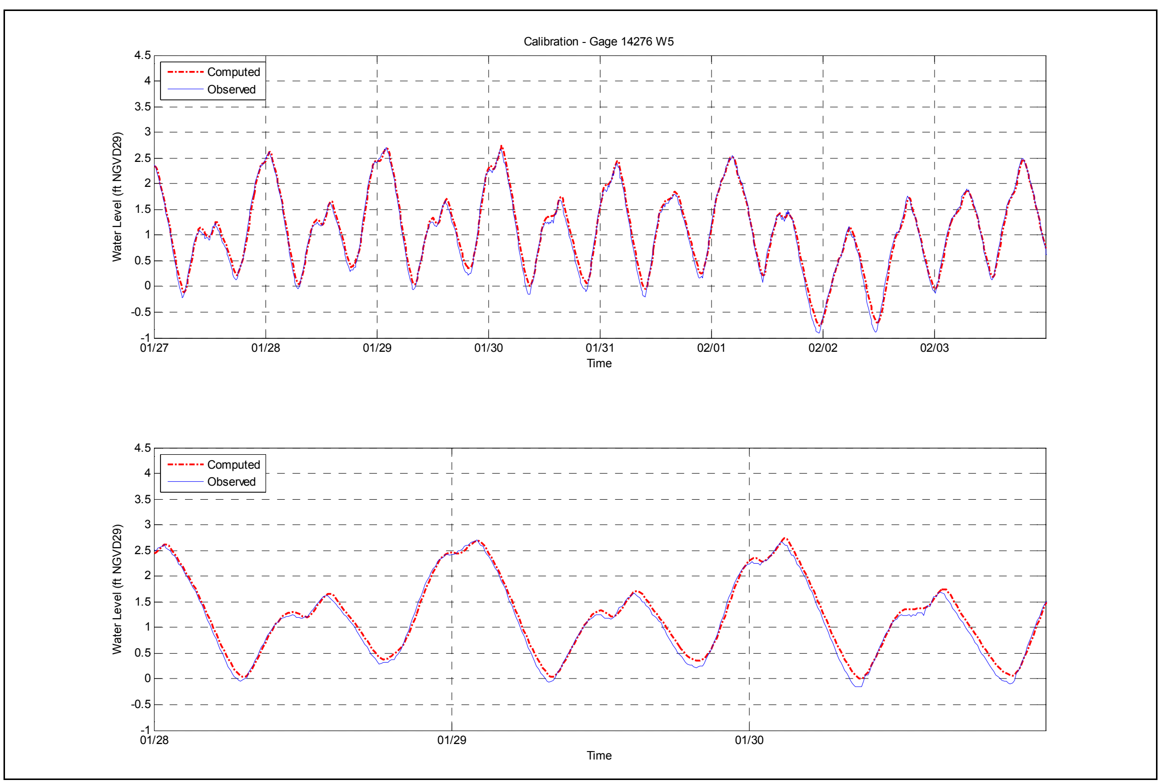


Figure V-12. Comparison of model output and measured tides for the TDR location in Quashnet River.

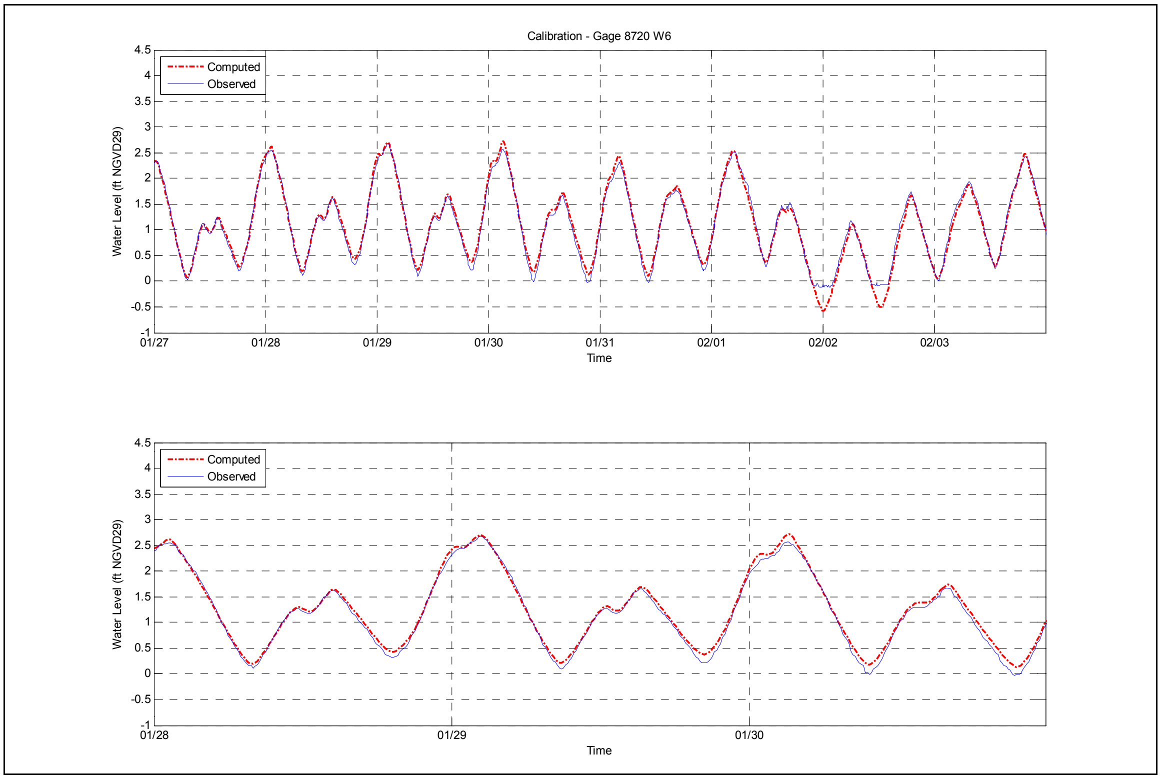


Figure V-13. Comparison of model output and measured tides for the TDR location in Hamblin Pond.

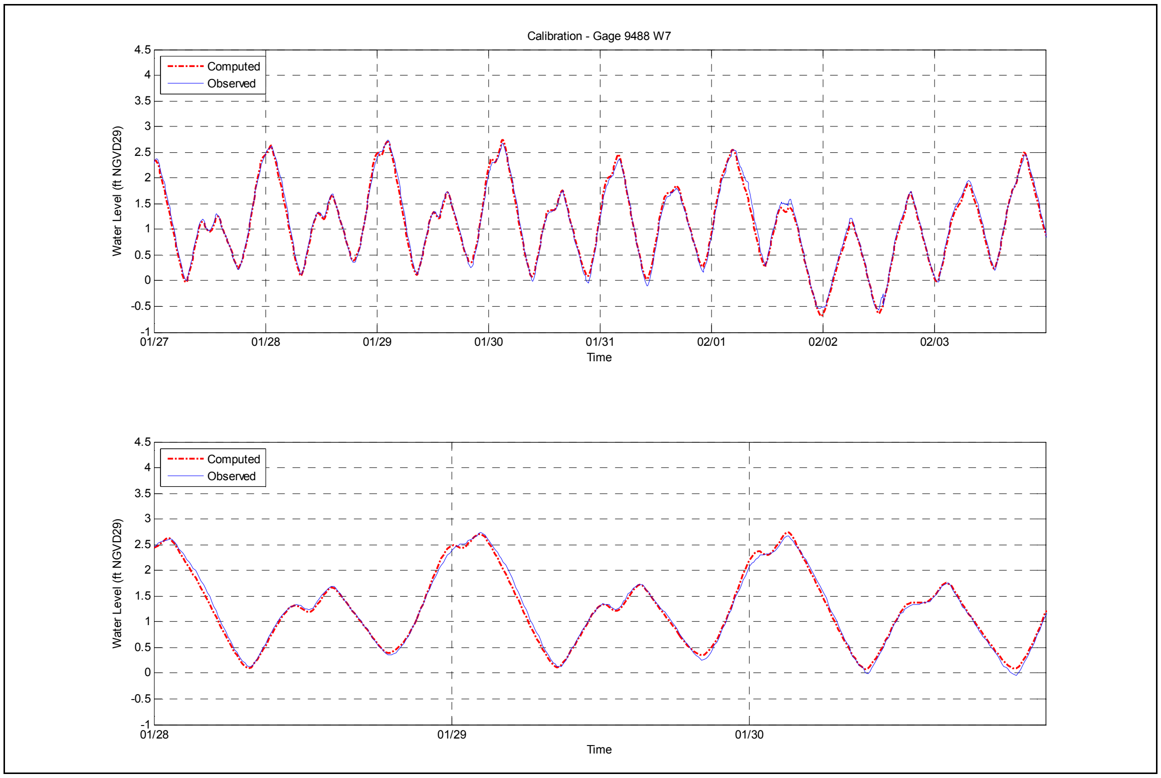


Figure V-14. Comparison of model output and measured tides for the TDR location in Great River.

Table V-6. Tidal constituents for measured water level data and calibrated model output for northern embayments.

Model calibration run						
Location	Constituent Amplitude (ft)				Phase (rad)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Eel Pond	0.87	0.17	0.09	0.28	-0.16	2.25
Childs River	0.85	0.15	0.08	0.27	-0.03	2.48
Waquoit Bay	0.85	0.14	0.08	0.27	0.02	2.57
Quashnet River	0.86	0.13	0.08	0.27	0.09	2.76
Hamblin Pond	0.81	0.06	0.06	0.27	0.39	-2.86
Great River	0.84	0.10	0.08	0.27	0.26	-3.14
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (rad)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Eel Pond	0.87	0.17	0.09	0.29	-0.21	2.15
Childs River	0.85	0.15	0.08	0.27	-0.09	2.37
Waquoit Bay	0.83	0.12	0.06	0.27	0.03	2.52
Quashnet River	0.89	0.16	0.09	0.28	-0.09	2.39
Hamblin Pond	0.82	0.08	0.06	0.27	0.28	-3.13
Great River	0.85	0.11	0.07	0.27	0.21	3.02
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Eel Pond	0.00	0.00	0.00	0.01	-5.9	-6.3
Childs River	-0.01	0.01	0.01	0.00	-7.1	-6.4
Waquoit Bay	-0.02	-0.02	-0.02	0.00	1.2	-2.9
Quashnet River	0.03	0.03	0.00	0.01	-21.4	-22.0
Hamblin Pond	0.01	0.01	0.00	0.01	-12.5	-15.6
Great River	0.02	0.01	-0.01	0.00	-6.4	-4.5

V.3.2.4 Model Circulation Characteristics

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

Examining the results from the model run of the Waquoit Bay shows flood velocities in the channels are slightly larger than velocities during maximum ebb. The maximum velocities occur in the entrance channels to Waquoit Bay and Eel Pond. At the two bridges over Back River, maximum depth-averaged flood velocities in the model are approximately 6.5 feet/sec, while maximum ebb velocities are about 5.5 feet/sec. In the inlet channel to Eel Pond, maximum depth averaged flood velocities are approximately 4.0 feet/sec, and maximum ebb velocities are 2.0 feet/sec. A close-up of the model output is presented in Figure V-15, which shows contours of velocity magnitude, along with velocity vectors which indicate the direction of flow, for a single model time-step, at the portion of the tide where maximum flood velocities occur.

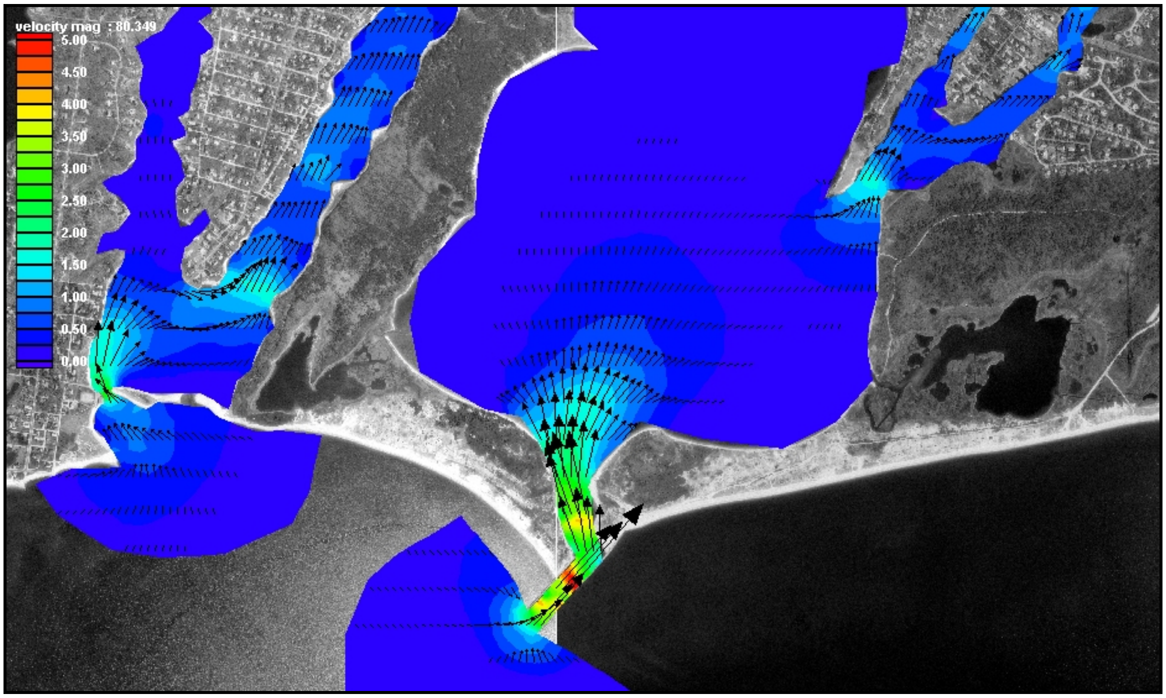


Figure V-15. Example of hydrodynamic model output for a single time step where maximum flood velocities occur for this tide cycle. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

In addition to depth averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. For the flushing analysis in the next section, flow rates were computed across six separate transects in the Waquoit Bay system: at entrance to Waquoit Bay, the entrance to Eel Pond, the channel going to Hamblin Pond and Great River, the entrance to Quashnet River, a transect across Childs River, and a transect across Eel Pond near the interest of Eel Pond and Childs River. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-16. Maximum flow rates occur during flood tides in this system, an indication that this estuary system is flood dominant, and likely a sediment sink (a system that accumulates sediment). During spring tides, the maximum flood flow rates reach 8,000 ft^3/sec through the Waquoit Bay inlet. Maximum ebb flow rates are less, approximately 6,000 ft^3/sec.

V.4. FLUSHING CHARACTERISTICS

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

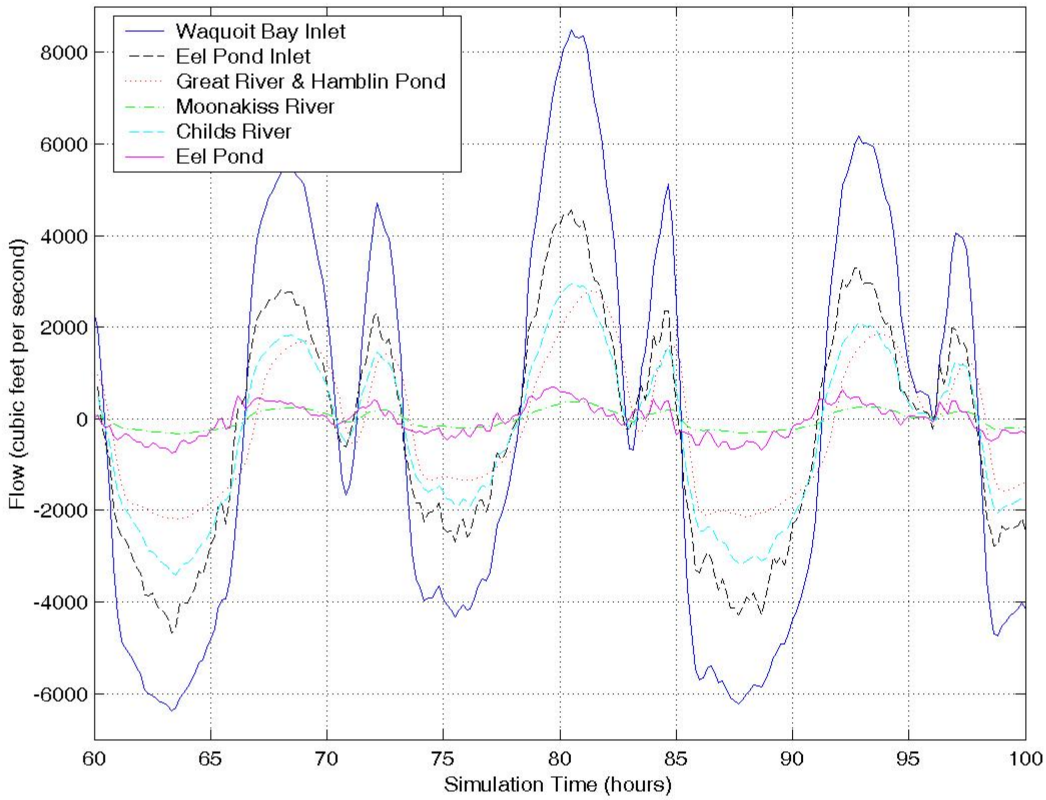


Figure V-16. Time variation of computed flow rates for six transects in the Waquoit Bay system. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Plotted time period represents three tide cycles (12.42 h cycle). Positive flow indicated flooding tide, while negative flow indicates ebbing tide.

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

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

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

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using Quashnet River as an example, the **system residence time** is the average time required for water to migrate from Quashnet River, through Waquoit Bay, and into Vineyard Sound, where the **local residence time** is the average time required for water to migrate from Quashnet River to just Waquoit Bay (not all the way out of the system). Local residence times for each sub-embayment are computed as:

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

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

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

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

Since the calibrated RMA-2 model simulated accurate two-dimensional hydrodynamics in the system, model results were used to compute residence times. Residence times were computed for the entire estuary, as well the main sub-embayments within 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.

Residence times were averaged for the tidal cycles comprising a representative 7.25 day period (14 tide cycles), and are listed in Table V-8. The modeled time period used to compute the flushing rates was different from the modeled calibration period, and included the transition from neap to spring tide conditions. Model divisions used to define the system sub-embayments include 1) the entire Waquoit Bay system, 2) Waquoit Bay, 3) Eel Pond, 4) Great River and Jehu Pond, 5) Hamblin Pond, 6) Quashnet River, 7) Childs River and Seapit River. The model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume. Since the 7.25-day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

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

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
System	380,320,000	97,247,064
Eel Pond (West Branch)	13,080,500	3,339,810
Great River	30,244,000	9,436,062
Jehu Pond	13,011,000	2,892,063
Hamblin Pond	29,237,000	9,050,124
Quashnet River	8,840,800	2,800,916
Childs River	9,821,500	1,481,343

Table V-8. Computed System and local residence times for embayments in the Waquoit Bay system.

Embayment	System Residence Time (days)	Local Residence Time (days)
System	2.02	
Eel Pond (West Branch)	58.93	2.03
Great River	20.86	1.66
Jehu Pond	68.05	2.33
Hamblin Pond	21.75	1.67
Quashnet River	70.27	1.63
Childs River	132.86	3.43

The computed flushing rates for the Waquoit system show that the system residence time is 2 days on average for the whole system. This suggests that the system has marginal tidal flushing. Local residence times tend to decrease for sub-embayments located further back in the system, which indicates that these areas flush more efficiently than the main system. This would suggest that water quality in these sub-embayments is more limited by watershed loading and water quality in the main basin of the Bay, rather than tidal flushing capacity.

The Childs River has the largest local residence time (3.4 days). This sub-embayment has a larger mean volume than the Quashnet River, which indicates that it has a greater average depth, since the surface area of the Childs River is less than the Quashnet River (and the tide range is essentially the same). Because the Childs River has a smaller surface area, its mean tide prism is also smaller. The combination of deeper average depths and smaller tide prism are what make the Childs River flush less efficiently than the Quashnet River.

Generally, possible errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. In this study, the most significant errors associated with the bathymetry data result from the process of interpolating the data to the finite element mesh, which was the basis for all the flushing volumes used in the analysis. In addition, limited topographic measurements were available on the marsh plains. 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 coast of Vineyard Sound typically is strong because of the local winds induce tidal mixing within the regional estuarine systems, the "strong littoral drift" assumption only will cause minor errors in residence time calculations. Based on our knowledge of estuarine processes, we estimate that the combined errors due to bathymetric inaccuracies represented in the model grid and the "strong littoral drift" assumption are within 10% to 15% of "true" residence times.

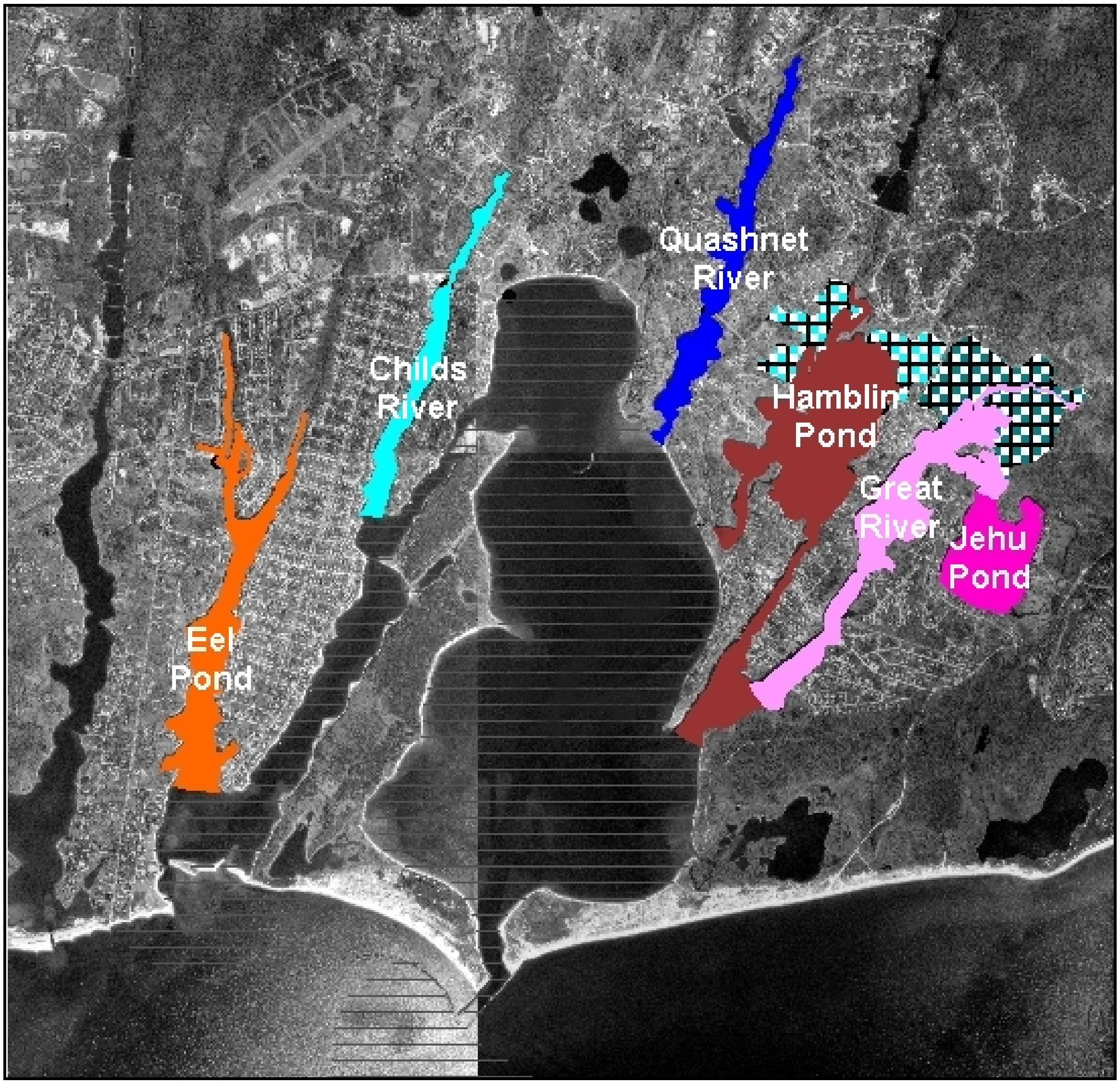


Figure V-17. Basins used to computed residence times for the Waquoit Bay system.

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 Waquoit Bay estuarine system. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayment

Extensive field measurements and hydrodynamic modeling of the embayment were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated model output representing the transport of water within the system embayment. Files of node locations and node connectivity for the RMA-2 model grid were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic output for the water quality model calibration was a 15 day period in January/February 2002. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model had reached a dynamic "steady state", and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayment

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

VI.1.3 Measured Nitrogen Concentrations in the Embayment

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in Figure VI-1, except for the offshore Vineyard Sound station which is located farther west closer to the Green pond Estuary. The multi-year averages present the "best" comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data is the minimum required to provide a baseline for MEP analysis. Nine years of data (collected between 2002 and 2010) were available for stations monitored by SMAST in the Waquoit Bay system.

Table VI-1. Water quality monitoring data, and modeled Nitrogen concentrations for the Waquoit Bay used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. “Data mean” values are calculated as the average of all data.

Sub-Embayment	Station ID	2002 mean	2003 mean	2004 mean	2005 mean	2006 mean	2007 mean	2008 mean	2009 mean	2010 mean	mean	s.d. all data	N	model min	model max	model mean
Jehu Pond	WB 1	0.593	0.576	0.638	0.481	0.570	0.608	0.619	0.515	0.671	0.581	0.096	36	0.598	0.676	0.630
Upper Great River	WB 2	0.679	0.558	0.714	0.442	0.569	0.594	0.599	0.513	0.620	0.585	0.125	33	0.369	0.642	0.535
Great/Little River	WB 3	0.624	0.505	0.562	0.447	0.487	0.568	0.480	0.482	0.568	0.535	0.109	34	0.294	0.567	0.427
Hamblin Pond	WB 4	0.567	0.460	0.536	0.451	0.513	0.485	0.583	0.471	0.552	0.517	0.079	37	0.428	0.577	0.521
FW Red Brook	WB 5	0.643	--	0.629	0.461	0.562	0.548	0.506	0.550	0.563	0.561	0.086	25	--	--	--
FW Quashnet River	WB 6	0.504	--	0.451	0.424	0.513	0.490	0.508	0.597	0.593	0.516	0.117	29	--	--	--
Upper Quashnet River	WB 7	0.670	0.574	0.653	0.504	0.739	0.638	--	0.626	0.597	0.632	0.196	24	0.701	0.750	0.725
Mid Quashnet River	WB 8	0.768	0.897	0.676	0.692	0.736	0.862	1.212	0.577	0.839	0.791	0.242	30	0.632	0.734	0.684
Lower Quashnet River	WB 9	0.586	0.580	0.694	0.524	0.674	0.698	0.792	0.655	0.598	0.633	0.127	32	0.491	0.684	0.592
Hamblin Pond Drain	WB 10	0.598	0.570	0.584	0.434	0.617	0.586	0.747	0.515	0.698	0.590	0.126	34	0.221	0.514	0.351
Seapit River	WB 11	0.501	0.540	0.617	0.543	0.585	0.460	0.594	0.531	0.491	0.528	0.078	33	0.293	0.469	0.382
Upper Waquoit Bay	WB 12	0.484	0.447	0.588	0.421	0.476	0.474	0.463	0.445	0.488	0.469	0.085	44	0.382	0.434	0.400
Lower Waquoit Bay	WB 13	0.412	0.376	0.496	0.357	0.398	0.378	0.386	0.400	0.424	0.392	0.057	45	0.279	0.430	0.300
Upper Childs River	CR 1	--	--	1.533	1.179	1.182	1.228	1.154	1.095	1.112	1.190	0.232	19	1.086	1.220	1.145
Mid Childs River	CR 2	--	--	0.926	0.790	0.822	0.936	1.067	0.720	1.009	0.888	0.337	23	0.531	0.753	0.651
Lower Childs River	CR 3	--	--	--	0.452	0.470	0.474	0.488	0.421	0.555	0.474	0.066	20	0.283	0.459	0.341
Upper Eel River	ER 1	--	--	--	0.690	0.771	0.765	0.719	0.730	0.774	0.742	0.132	20	0.526	0.819	0.669
Lower Eel River	ER 2	--	--	--	0.593	0.541	0.617	0.649	0.553	0.760	0.622	0.138	21	0.301	0.651	0.428
Eel Pond	ER 3	--	--	--	0.454	0.362	0.411	0.364	0.376	0.455	0.404	0.059	19	0.280	0.445	0.307
Vineyard Sound	VS										0.280	0.065	196	--	--	--

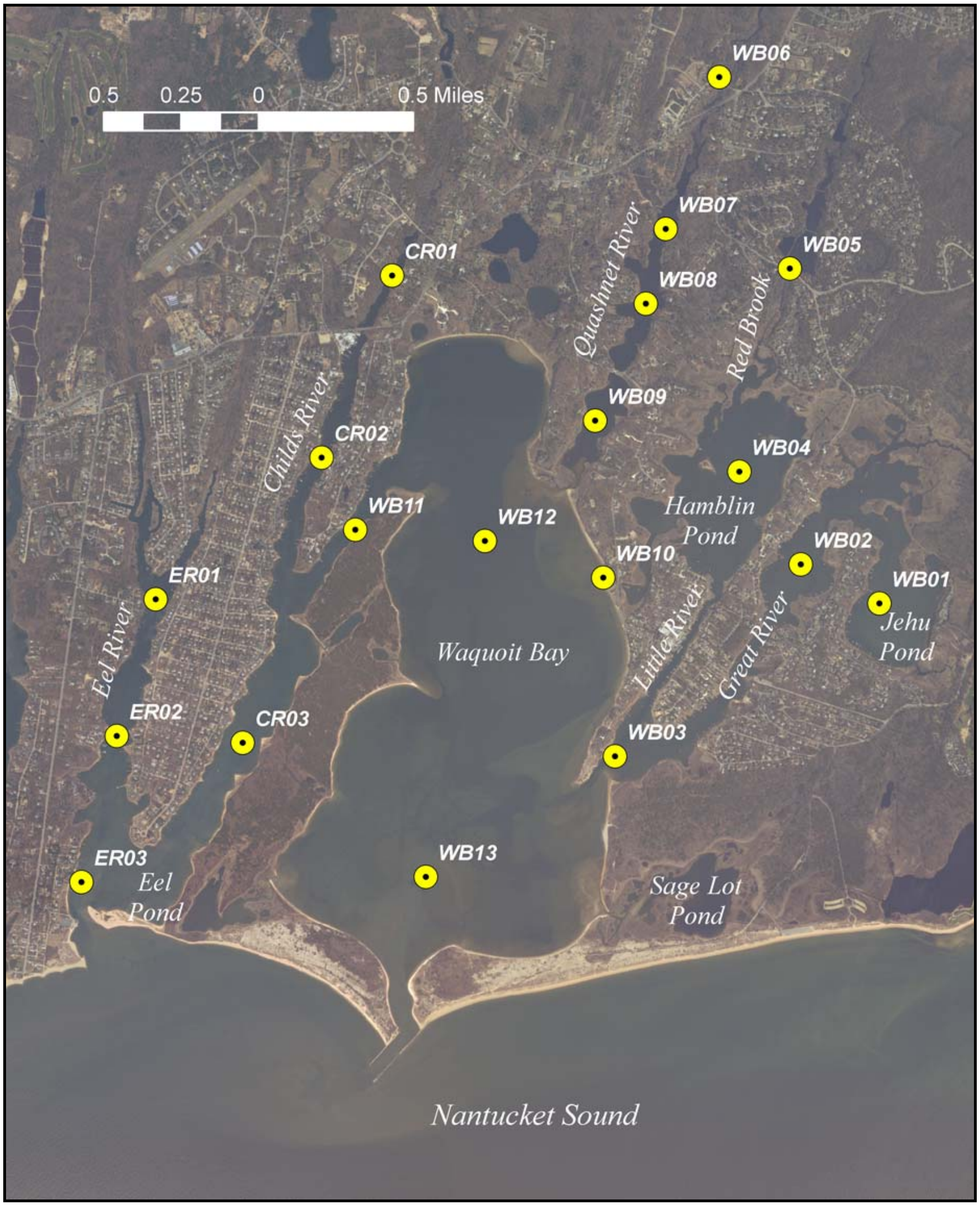


Figure VI-1. Estuarine water quality monitoring station locations in the Waquoit Bay estuary system. Station labels correspond to those provided in Table VI-1.

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 throughout the Waquoit Bay estuary system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of the Waquoit Bay estuarine system. Like RMA-2 numerical code, RMA-4 is a two-dimensional depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod embayments, including systems in Yarmouth (Howes *et al*., 2010); Martha's Vineyard (Howes *et al*., 2010) and Chatham, MA (Howes *et al*., 2003).

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

VI.2.1 Model Formulation

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

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

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

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

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

VI.2.2 Water Quality Model Setup

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

Based on groundwater recharge rates from the USGS, the hydrodynamic model was set-up to include ground water flowing into the system from the watersheds. Cumulative average direct rainfall, ground water and surface water inputs to the model are listed in Table VI-2. For the fresh water portions of the Childs and Quashnet rivers, flow rates were determined using summertime averages of available measured flow data from SMAST.

Table VI-2. Total ground water, surface water, and direct rain inputs included in the hydrodynamic and water quality model runs of the Waquoit Bay estuary system.

System watershed	ft^3/day	$m^{3/day}$
Jehu Pond	80,371	2,276
Great River	178,525	5,055
Hamblin Pond	33,721	955
Red Brook - fresh water	319,058	9,035
Little River	16,539	468
Quashnet River- fresh water	1,179,316	33,395
Quashnet River -lower	93,794	2,656
Waquoit Bay	381,353	10,799
Seapit River	14,053	398
Childs River - fresh water	273,759	7,752
Childs River -lower	239,925	6,794
Eel Pond - west	339,370	9,610
Eel Pond - south	84,130	2,382
Eel Pond - east	125,216	3,546

For the model, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 14 day (336hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the Waquoit Bay system.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed direct atmospheric deposition load for the west branch of Eel Pond was evenly distributed at grid cells that formed the perimeter of the embayment. Benthic regeneration load was distributed among the remainder of non-watershed designated grid cells in the interior portion of each basin.

The loadings used to model present conditions in the Waquoit Bay system are given in Table VI-3. 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 coverage, when present), resulting in a total flux for each embayment (as listed in Table VI-3). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For present conditions, the benthic flux is generally negative with some of the inner reaches of the system having a positive benthic flux (i.e., the eastern branch of Eel Pond, the Seapit River and the sub-systems in Mashpee).

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary was 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 concentrations in Nantucket Sound were set at 0.280 mg/L, based on SMAST data from the Nantucket Sound. The open boundary total nitrogen concentration represents long-term average summer concentrations found within Nantucket Sound.

VI.2.4 Model Calibration

Calibration of the total nitrogen model proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (E) values were varied through the modeled system by setting different values of E for each grid material type, as designated in Figure V-8. Observed values of E (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent areas of Waquoit Bay (coves and marsh) require values of E that are lower compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979). Observed values of E in these calmer areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of E used in each sub-embayment of the modeled systems are presented in Table VI-4. 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 error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

Table VI-3. Sub-embayment loads used for total nitrogen modeling of the Waquoit Bay system, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions.**

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Waquoit Bay	2.088	11.956	-69.126
Childs River - upper	12.019	0.455	-7.437
Eel Pond - east branch	2.170	1.011	26.004
Eel Pond - south basin	0.523	0.663	-5.650
Eel Pond - west branch	16.337	0.890	-4.383
Quashnet River	2.773	0.252	11.996
Hamblin Pond	4.381	1.529	7.890
Little River	1.096	0.156	3.439
Jehu Pond	3.912	0.674	9.854
Great River	3.671	1.307	19.679
Sage Lot Pond	2.753	0.471	-3.086
Childs River - freshwater	10.622	-	-
Moonakiss River (upper Quashnet)	20.507	-	-
Red Brook -freshwater	8.014	-	-
Total	**90.866**	**19.364**	**-10.821**

Table VI-4. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for the Waquoit Bay system. Embayment divisions correspond to those shown in Figure V-8.

Embayment Division	E m^2/sec
Nantucket Sound	1.0
Waquoit Bay – main basin	0.5
Eel River	3.0
Eel Pond	2.0
Childs River - north of Rt. 28	1.5
Childs River - upper	2.0
Childs River - lower	1.0
Seapit River	0.5
Quashnet River - lower	10.0
Quashnet River - upper	5.0
Hamblin Pond marsh plain	0.5
Hamblin Pond	2.0
Hamblin Pond outlet	0.5
Great River	20.0
Great River marsh plain	1.0
Jehu Pond	5.0
Little River	20.0
Sage Lot Pond	1.0

Comparisons between 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 SMAST monitoring stations.

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

Also presented in this figure are unity plot comparisons of measured data versus modeled target values for the system. The model fit is good for the Waquoit Bay system, with rms error of 0.075 mg/L and an R^2 correlation coefficient of 0.86.

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

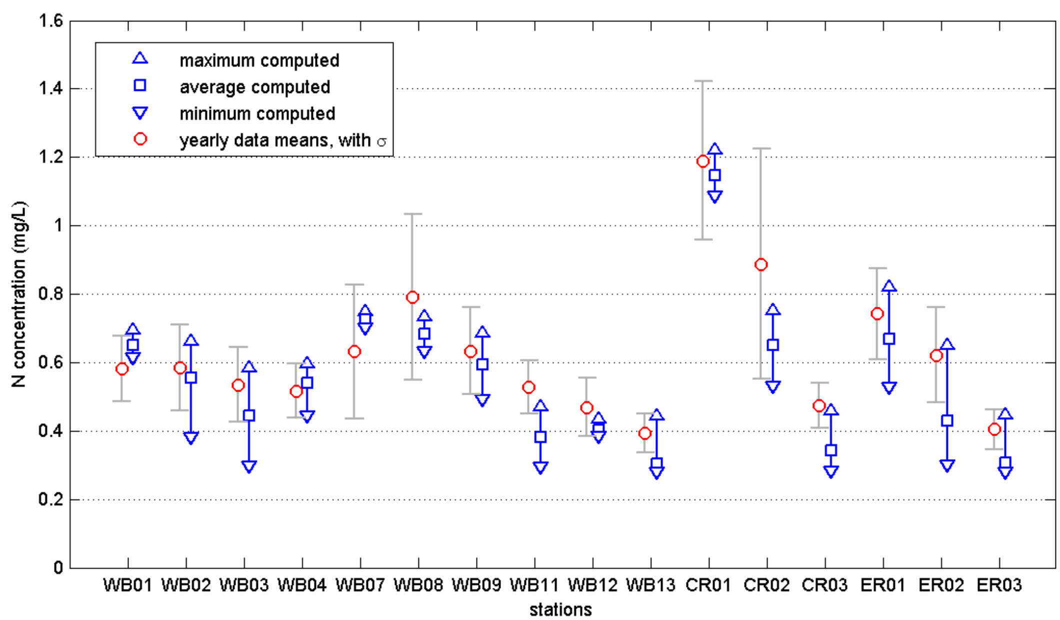


Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Waquoit Bay system. Station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation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

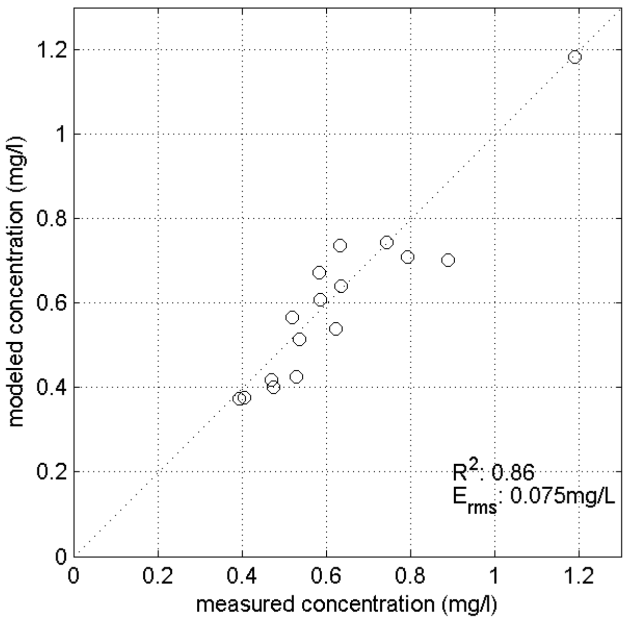


Figure VI-3. Model calibration target values are plotted against measured concentrations, together with the unity line.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Waquoit Bay estuary system using salinity data collected at the same stations as the nitrogen data. The only required inputs into the RMA4 salinity model of each system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, and groundwater inputs. The open boundary salinity was set at 31.6 ppt. For groundwater inputs salinities were set at 0 ppt. The total freshwater input used for the model (including rain, ground water and surface water flows) was 5,131,300 ft^3/day (145,300 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed evenly within each watershed through grid cells that formed the perimeter along each watershed's land boundary.

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. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in the Waquoit Bay estuary. The rms error of the models was 2.6 ppt, and correlation coefficient was 0.89. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical systems.

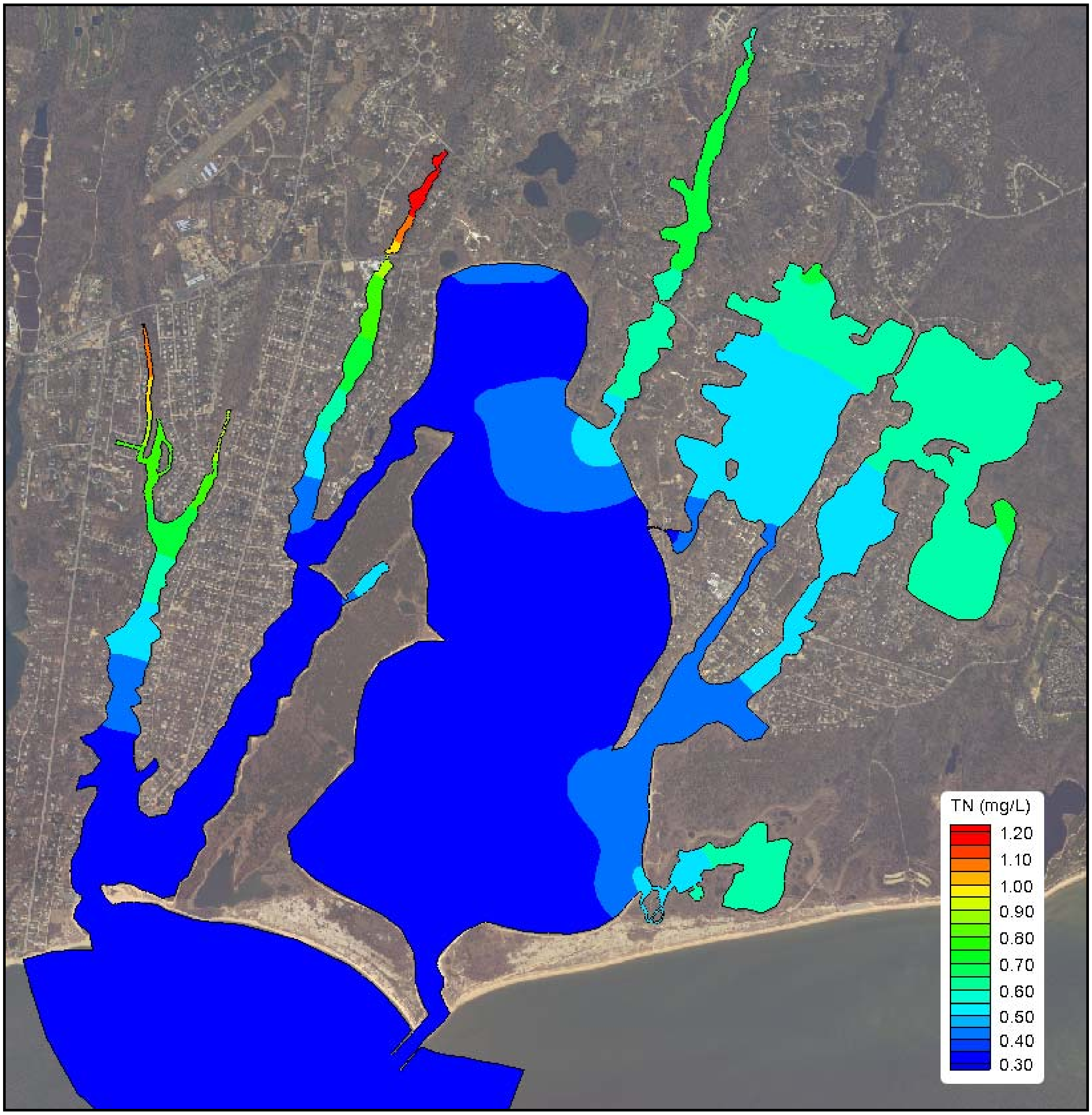


Figure VI-4. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for the Waquoit Bay system.

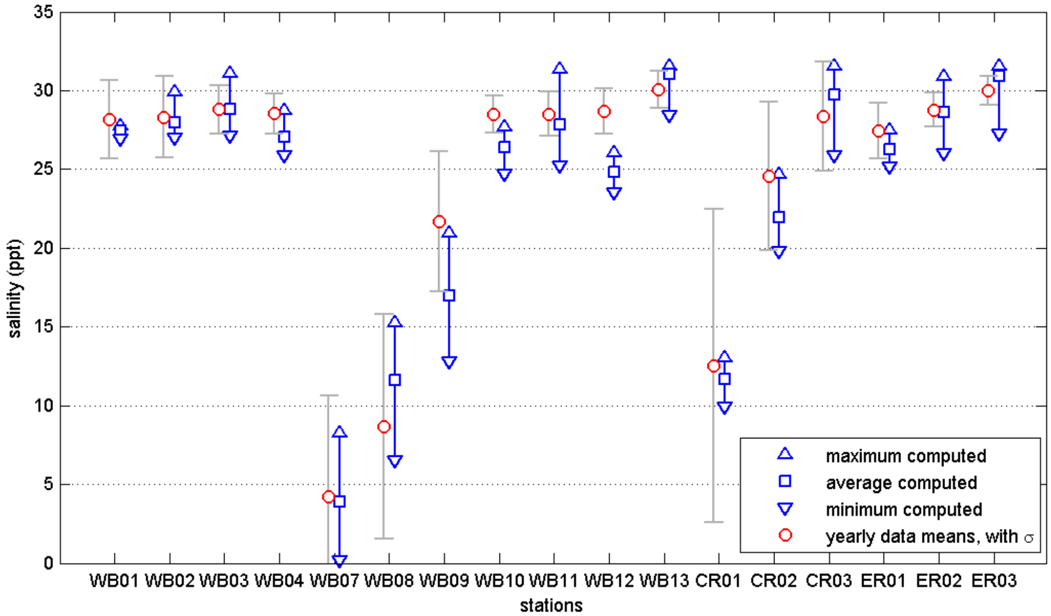


Figure VI-5. Comparison of measured and calibrated model output at stations in Waquoit Bay. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers),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

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the embayment system, two standard water quality modeling scenarios were run: a “build-out” scenario based on potential development (described in more detail in Section IV) and a “no anthropogenic load” or “no load” scenario assuming only atmospheric deposition on the watershed and sub-embayment, as well as a natural forest within each watershed. Comparisons of the alternate watershed loading analyses are shown in Table VI-5. 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.

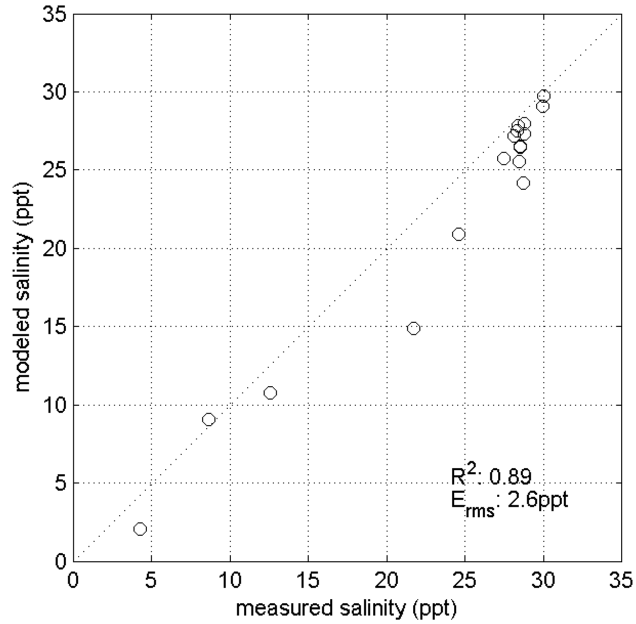


Figure VI-6. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line.

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be a increase in watershed nitrogen load to the Waquoit Bay estuarine system as a result of potential future development. Specific watershed areas would experience large load increases, for example the loads to the west branch of Eel Pond would increase 44% from the present day loading levels. For the no load scenarios, a majority of the load entering the watershed is removed; therefore, the load is significantly lower than existing conditions by nearly 90% overall.

For the build-out scenario, a breakdown of the total nitrogen load entering Waquoit Bay's attached sub-embayments is shown in Table VI-6. 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:

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

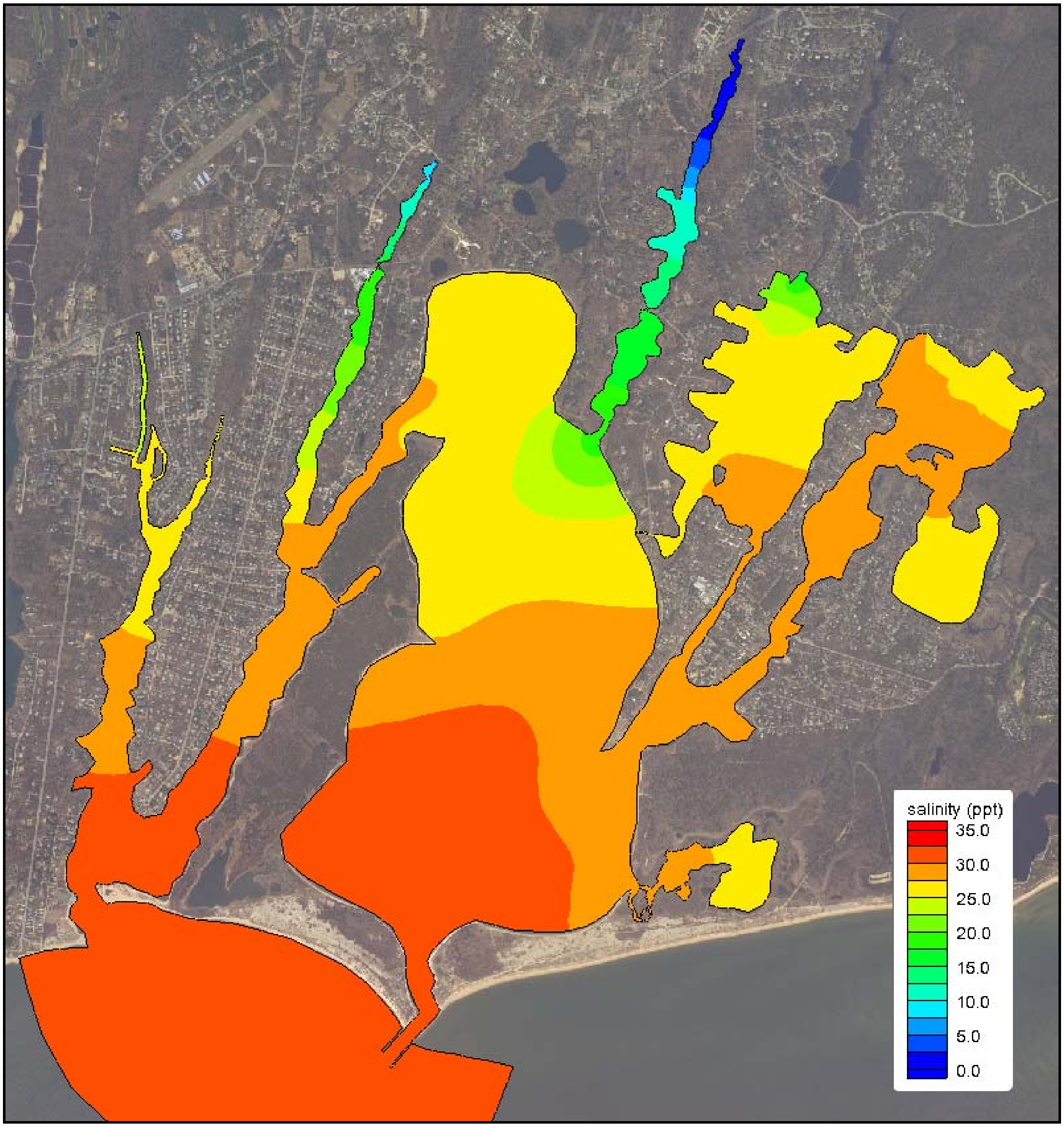


Figure VI-7. Contour plots of modeled salinity (ppt) from the model of the Waquoit Bay system.

Table VI-5. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Waquoit Bay system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	build out (kg/day)	build out % change	no load (kg/day)	no load % change
Waquoit Bay	2.088	3.123	+49.6%	0.422	-79.8%
Childs River - upper	12.019	13.732	+14.2%	0.485	-96.0%
Eel Pond - east branch	2.170	2.255	+3.9%	0.085	-96.1%
Eel Pond - south basin	0.523	0.537	+2.6%	0.016	-96.9%
Eel Pond - west branch	16.337	23.542	+44.1%	0.707	-95.7%
Quashnet River	2.773	3.362	+21.2%	0.523	-81.1%
Hamblin Pond	4.381	5.595	+27.7%	0.268	-93.9%
Little River	1.096	1.444	+31.8%	0.027	-97.5%
Jehu Pond	3.912	4.222	+7.9%	0.140	-96.4%
Great River	3.671	4.145	+12.9%	0.312	-91.5%
Sage Lot Pond	2.753	3.660	+32.9%	0.693	-74.8%
Childs River	10.622	26.118	+145.9%	0.978	-90.8%
Moonakiss River	20.507	35.260	+71.9%	4.222	-79.4%
Red Brook	8.014	10.975	+37.0%	0.449	-94.4%
SYSTEM TOTAL	**90.866**	**137.970**	**+51.8%**	**9.329**	**-89.7%**

Table VI-6. Build-out sub-embayment and surface water loads used for total nitrogen modeling of the Waquoit Bay system, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Waquoit Bay	3.123	11.956	-79.488
Childs River - upper	13.732	0.455	-10.100
Eel Pond - east branch	2.255	1.011	31.826
Eel Pond - south basin	0.537	0.663	-7.895
Eel Pond - west branch	23.542	0.890	-5.819
Quashnet River	3.362	0.252	15.228
Hamblin Pond	5.595	1.529	9.470
Little River	1.444	0.156	4.077
Jehu Pond	4.222	0.674	9.854
Great River	4.145	1.307	23.666
Sage Lot Pond	3.660	0.471	-3.464
Childs River - freshwater	26.118	-	-
Moonakiss River (upper Quashnet)	35.260	-	-
Red Brook -freshwater	10.975	-	-
Total	**137.970**	**19.364**	**-12.645**

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of Waquoit Bay was run to determine nitrogen concentrations within each sub-embayment (Table VI-7). Total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most in at the upper Childs River monitoring station (CR01), with the water quality station in the pond showing a 127% increase in total nitrogen over background. The stations across the Waquoit Bay estuary show steady increase in nitrogen from the inlet to the head of the system. Color contours of model output for the build-out scenario are present in Figure VI-8. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-4, which allows direct comparison of nitrogen concentrations between loading scenarios.

Table VI-7. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change over the Vineyard Sound background concentration (0.280 mg/L), for the Waquoit Bay system. Sentinel threshold stations from Chapter VIII are shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Jehu Pond	WB01	0.630	0.693	+17.9%
Great River - upper	WB02	0.535	0.593	+22.7%
Great River - mouth	WB03	0.427	0.470	+29.1%
Hamblin Pond	WB04	0.521	0.591	+29.3%
Quashnet River - upper	WB07	0.725	1.150	+95.7%
Quashnet River - middle	WB08	0.684	1.013	+81.5%
Quashnet River - lower	WB09	0.592	0.840	+79.5%
Hamblin Pond outlet	WB10	0.351	0.426	+105.5%
Seapit River	WB11	0.382	0.461	+77.6%
Waquoit Bay - upper basin	**WB12**	**0.400**	**0.514**	**+94.3%**
Waquoit Bay - lower basin	WB13	0.300	0.308	+39.7%
Childs River - upper	CR01	1.145	2.242	+126.8%
Childs River - middle	**CR02**	**0.651**	**1.003**	**+95.0%**
Childs River - lower	CR03	0.341	0.383	+67.9%
Eel River - upper	**ER01**	**0.669**	**0.849**	**+46.3%**
Eel River - middle	ER02	0.428	0.501	+49.7%
Eel Pond	ER03	0.307	0.322	+54.9%

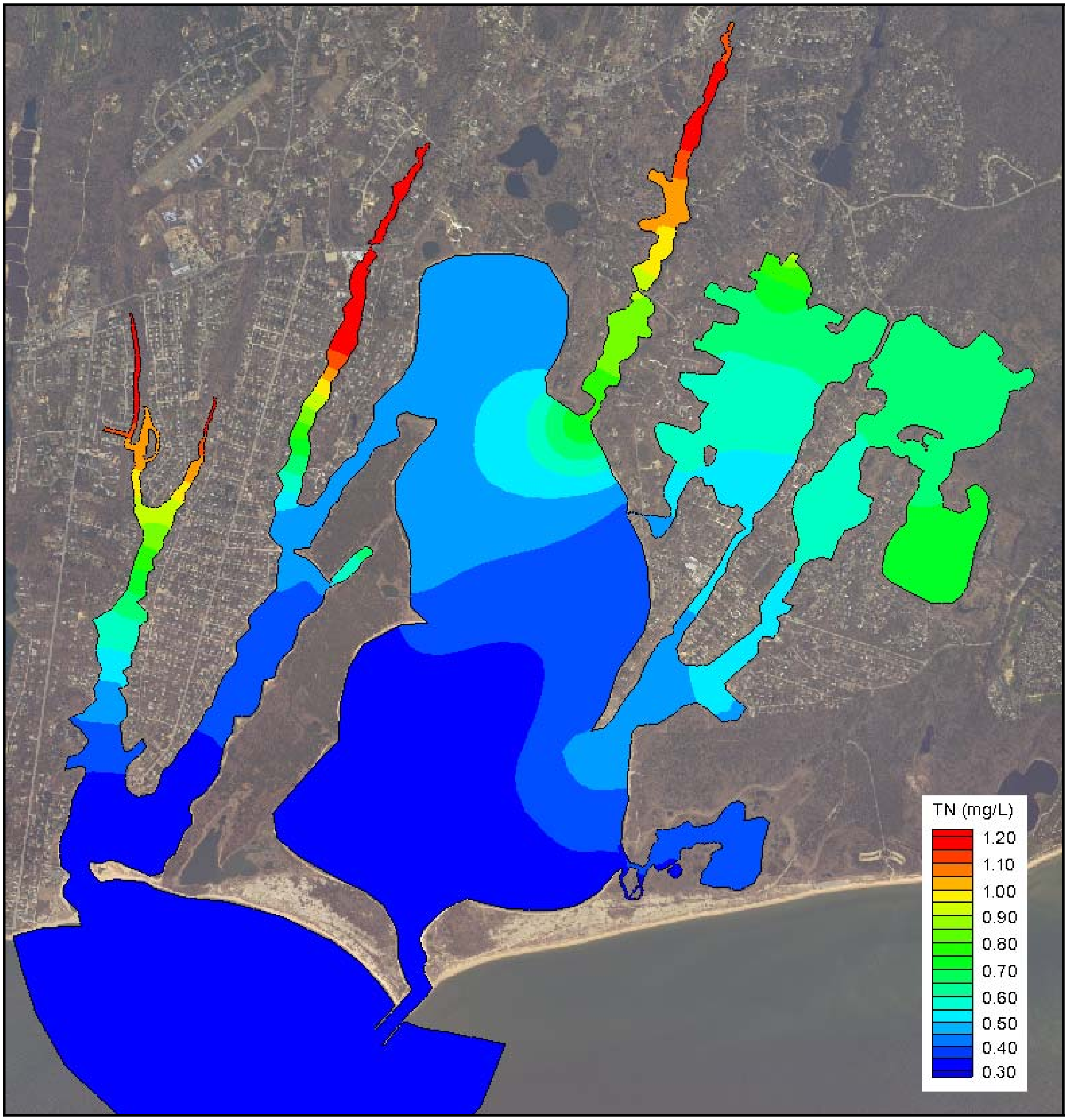


Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in Waquoit Bay system, for projected build-out loading conditions, and bathymetry.

VI.2.6.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering each sub-embayment for the no anthropogenic load ("no load") scenario is shown in Table VI-8. 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-8. "No anthropogenic loading" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of Waquoit Bay system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Waquoit Bay	0.422	11.956	-51.181
Childs River - upper	0.485	0.455	-2.827
Eel Pond - east branch	0.085	1.011	15.929
Eel Pond - south basin	0.016	0.663	-3.930
Eel Pond - west branch	0.707	0.890	-1.900
Quashnet River	0.523	0.252	6.399
Hamblin Pond	0.268	1.529	5.150
Little River	0.027	0.156	2.337
Jehu Pond	0.140	0.674	5.991
Great River	0.312	1.307	12.682
Sage Lot Pond	0.693	0.471	-2.431
Childs River - freshwater	0.978	-	-
Moonakiss River (upper Quashnet)	4.222	-	-
Red Brook -freshwater	0.449	-	-
Total	**9.329**	**19.364**	**-13.781**

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Again, total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was significant as shown in Table VI-9, with reductions ranging from 58% occurring at Jehu Pond to greater than 100% reduction in total nitrogen in the Quashnet River. Results for each system are shown pictorially in Figure VI-9.

Table VI-9. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change over the Nantucket Sound background concentration (0.280 mg/L), for the Waquoit Bay system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). Sentinel threshold stations from Chapter VIII are shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Jehu Pond	WB01	0.630	0.422	-59.5%
Great River - upper	WB02	0.535	0.376	-62.4%
Great River - mouth	WB03	0.427	0.324	-70.4%
Hamblin Pond	WB04	0.521	0.343	-73.8%
Quashnet River - upper	WB07	0.725	0.214	-114.9%
Quashnet River - middle	WB08	0.684	0.264	-103.9%
Quashnet River - lower	WB09	0.592	0.268	-103.8%
Hamblin Pond outlet	WB10	0.351	0.238	-158.7%
Seapit River	WB11	0.382	0.271	-108.4%
Waquoit Bay - upper basin	**WB12**	**0.400**	**0.248**	**-126.3%**
Waquoit Bay - lower basin	WB13	0.300	0.283	-84.4%
Childs River - upper	CR01	1.145	0.177	-111.9%
Childs River - middle	**CR02**	**0.651**	**0.227**	**-114.3%**
Childs River - lower	CR03	0.341	0.280	-99.3%
Eel River - upper	**ER01**	**0.669**	**0.283**	**-99.3%**
Eel River - middle	ER02	0.428	0.280	-100.1%
Eel Pond	ER03	0.307	0.281	-97.8%

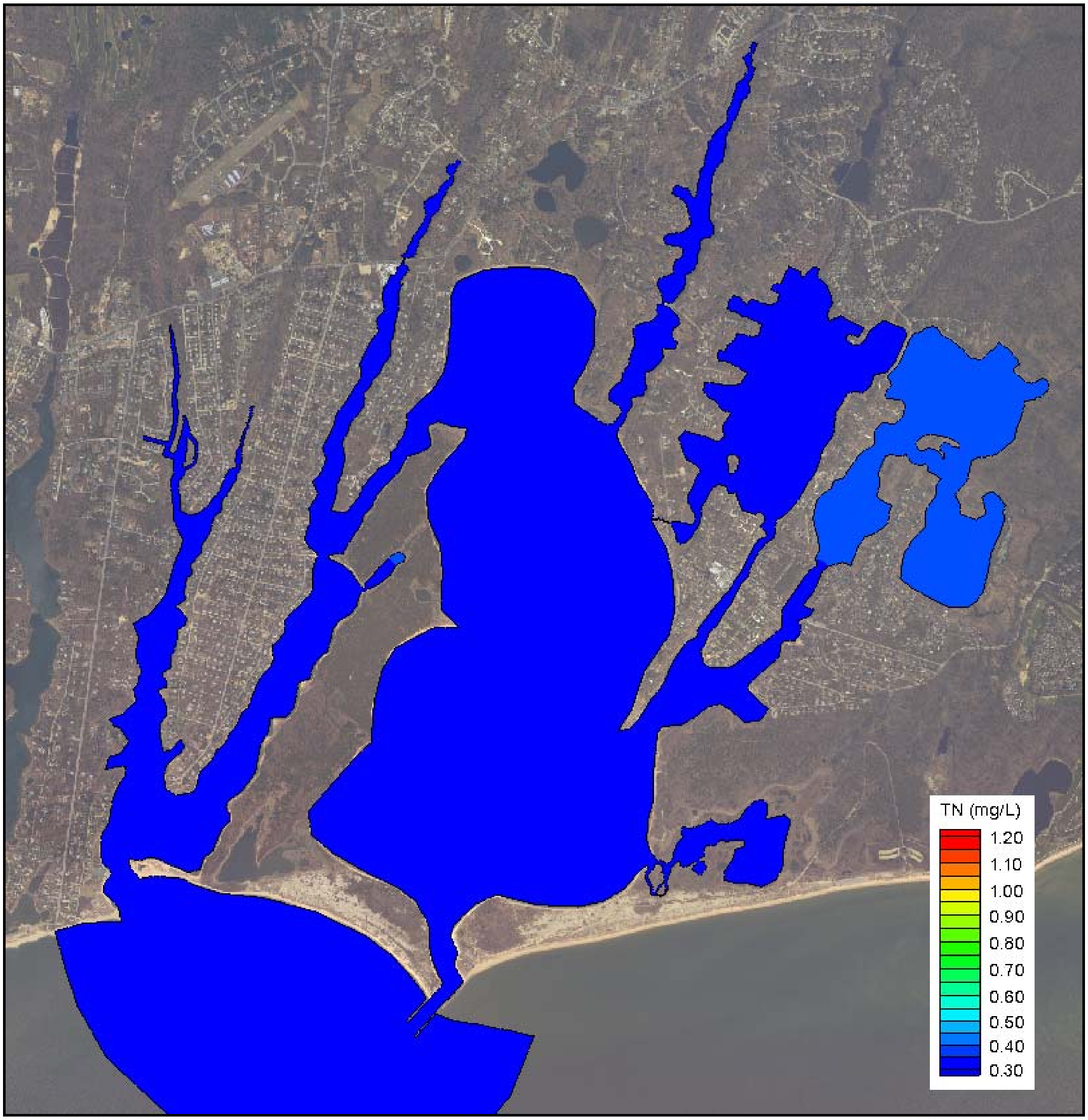


Figure VI-9. Contour plots of modeled total nitrogen concentrations (mg/L) in Waquoit Bay system, for no anthropogenic loading conditions, and bathymetry.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters, as well as the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For each of the component sub-embayments comprising the Waquoit Bay System, inclusive of the eastern sub-embayments of Waquoit Bay (Quashnet River, Hamblin Pond/Little River and Jehu Pond/Great River) and the western sub-embayments of Eel Pond and Childs River, the MEP habitat assessment is based upon data from the water quality monitoring database, including time-series monitoring of oxygen and chlorophyll-*a*, and our surveys of eelgrass distribution, benthic animal communities and sediment characteristics. Time-series dissolved oxygen and chlorophyll-*a* records were obtained during the summers of 2001 and 2002 for the eastern sub-embayment of Hamblin and Jehu Ponds as well as in the summer of 2005 for the main basin of Waquoit Bay and the Eel Pond and Childs River sub-embayments. The water quality data (e.g. chlorophyll) was collected by the Mashpee Water Quality Monitoring Program and the WBNERR sponsored BayWatcher Program. Time-series oxygen data were available from the WBNERR System-Wide Monitoring Program (SWMP) for Sage Lot Pond. These data form the basis of an assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for these systems (Section VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen thresholds determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll-*a* (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly, and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed dissolved oxygen sensors within the upper and lower portions of the main basin of Waquoit Bay as well as the upper portions of both the east and west branches of Eel Pond and the Childs River and the upper tributary sub-embayments on the east shore of the main Bay (Quashnet River and Hamblin Pond). These moorings were deployed for a minimum of 30 days to record the frequency and duration of low oxygen conditions during the critical summer period. A dissolved oxygen sensor was also deployed in Jehu Pond, but failed to yield usable data. However, anoxic conditions were measured in Jehu Pond during previous MEP field data collection, indicating that severe oxygen depletion was occurring periodically in this basin.

The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the main basin of Waquoit Bay as well as the eastern and western sub-embayments to the Waquoit Bay System was conducted for comparison to historic records (DEP Eelgrass Mapping Program, C. Costello). In addition, results of detailed mapping studies of these estuaries conducted during 1987-1992 were also available for evaluating temporal trends (Short and Burdick 1996). 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. Analysis of inorganic N/P molar ratios within the water column of the major basins comprising the Waquoit Bay Embayment System support the contention that nitrogen is the nutrient to be managed. The ratio in the all of the sub-embayment waters was <4, with only the freshwater influenced uppermost regions of the Quashnet River, Eel River and Childs River being ~10. As such, virtually all of the estuarine waters of this system are far below the Redfield Ratio value (16) indicating that nitrogen additions will increase phytoplankton production in this system. Within the overall Waquoit Bay system, temporal changes in eelgrass distribution provides a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing due to new inlet formation) in nutrient enrichment and whether the nitrogen assimilative capacity (level of nitrogen enrichment that can be tolerated without a decline in habitat quality) of a basin has been exceeded.

In areas that do not support eelgrass beds, benthic animal indicators were used to assess the level of habitat health from “healthy” (low organic matter loading, high D.O.) to highly stressed or “Significantly Degraded” (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 and stable 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 maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Waquoit Bay System, including Waquoit Bay, Eel Pond, Childs River, the Quashnet River, Hamblin Pond/Little River and Jehu Pond/Great River sub-embayments, 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 it is that 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 which consume oxygen from the water column 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. 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 placed within key regions within the main basin of Waquoit Bay as well as the eastern and western sub-embayment system (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and checked with standard oxygen mixtures. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each mooring was serviced and calibration samples collected about biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the instrument mooring data from the Quashnet River and Hamblin Pond sub-embayments were collected during the summer of 2002. The DO/CHLA mooring data for the main basin (3 moorings) of Waquoit Bay and Eel Pond (1 mooring) and Childs River (1 mooring) were collected in the summer of 2007. In addition, oxygen records from summers 2002-2006 were provided by WBNERR for Sage Lot Pond. Since the moored instrument in Jehu Pond did not yield usable data, the MEP analysis of this basin had to rely on traditional "grab" samples for dissolved oxygen (and chlorophyll-*a*). These samples are typically collected in the early morning, when oxygen levels are at or near their lowest point for a day. These oxygen data were collected by WBNERR's Baywatch Program and the Mashpee Water Quality Monitoring Program overseen by Coastal Systems Program-SMAST Staff.

VII.2.1 Bottom water Dissolved Oxygen Results for Waquoit Bay (Main Basin)

Similar to other embayments in southeastern Massachusetts, the Waquoit Bay Embayment System evaluated in this MEP assessment bottom water oxygen concentrations showed high frequency variation related primarily to diurnal and sometimes tidal influences within all of the component sub-embayments. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. Oxygen excursions result from oxygen consumption (night) and production (day) primarily by phytoplankton within the estuarine waters. Additional oxygen uptake results from the microbial decay of organic matter, which in the case of the Waquoit Bay Estuary, is mainly from decomposition of extensive macroalgal mats as well as phytoplankton in the water column and after settling to bottom sediments. Oxygen levels in estuaries typically cannot be managed directly, but rather through management of nitrogen levels and mitigation of any direct organic matter inputs (e.g. outfalls).

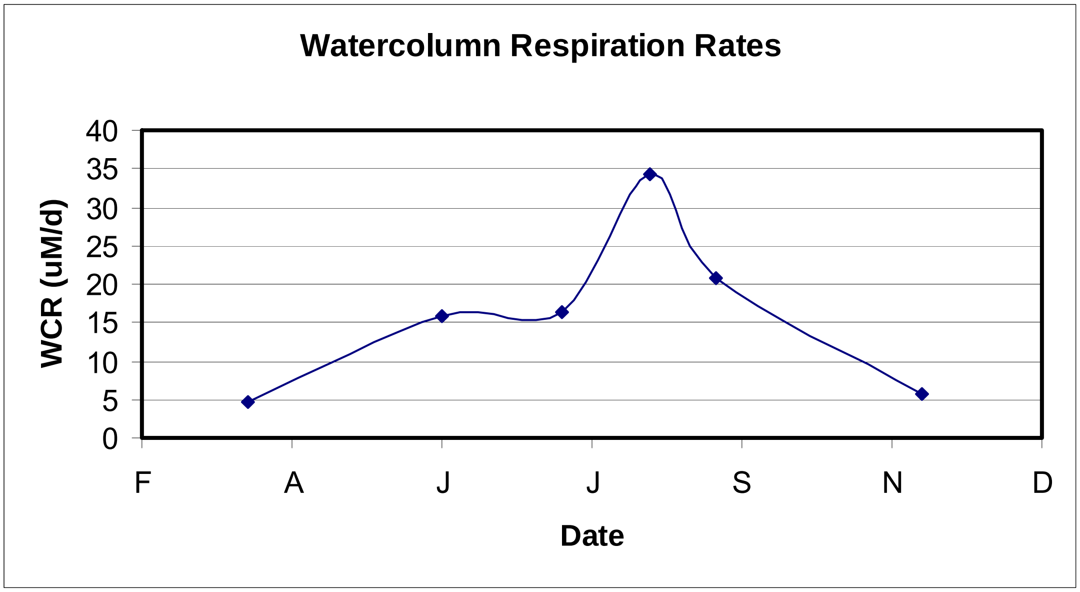


Figure VII-1. Average water column respiration rates from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

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. These continuous records were also complemented by oxygen data collected by the Waquoit Bay National Estuarine Research Reserve (WBNERR) SWMP mooring in Sage Lot Pond from 2002-2006.

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 22-42 day deployment period that these parameters were below or above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels within the main Basin (north and south) of Waquoit Bay indicate high levels of nutrient enrichment and impaired habitat quality (Figures VII-3, VII-5, VII-7). The oxygen data are consistent with high organic matter loads and the moderate levels of phytoplankton biomass (chlorophyll-*a* levels) are indicative of nitrogen enrichment of this estuarine basin. The large daily excursions in oxygen concentration in the main basin of Waquoit Bay, from the head (~3 mg L^{-1}) to middle (5-7 mg L^{-1}) to the lower portion close to the inlet (5 mg L^{-1}), are clear indications of significant organic matter enrichment and estuarine waters with an unstable oxygen balance. It is also clear from the macroalgal algal accumulations in the southern reach of the main basin that these primary producers are contributing to the observed excursions.

Figure VII-2. Aerial Photograph of the Waquoit Bay Embayment System within the Towns of Falmouth and Mashpee showing locations of Dissolved Oxygen mooring deployments conducted in summer 2002 (Quashnet River and Hamblin Pond) and in the summer of 2007 (main basin Waquoit Bay, Childs River and Eel Pond). Yellow symbols show instrument locations. Green symbols are WBNERR deployed long term DO mooring stations.

The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration throughout Waquoit Bay and its sub-embayments is further evidence of nitrogen enrichment at a level consistent with habitat degradation.

Table VII-1. Duration (percent of deployment time) that bottom water dissolved oxygen levels were below various benchmark levels within the main basin of the overall Waquoit Bay system. “Mean” represents the average duration of each event over the benchmark level and “S.D.” its standard deviation. Data collected by the Coastal Systems Program, SMAST.

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Waquoit WAQ33	**8/15/2007**	**9/26/2007**	**42.2**	**15.30**	**10.07**	**4.84**	**2.09**
			Mean	0.40	0.25	0.19	0.15
			Min	0.02	0.02	0.02	0.03
			Max	1.61	0.73	0.51	0.44
			S.D.	0.34	0.21	0.17	0.11
Waquoit WAQ24	**7/4/2007**	**7/26/2007**	**22.2**	**3.91**	**1.01**	**0.00**	**0.00**
			Mean	0.20	0.13	N/A	N/A
			Min	0.01	0.01	0.00	0.00
			Max	0.73	0.26	0.00	0.00
			S.D.	0.19	0.10	N/A	N/A
Waquoit WAQ27	**7/3/2007**	**7/26/2007**	**22.6**	**8.41**	**3.28**	**0.77**	**0.18**
			Mean	0.32	0.16	0.10	0.09
			Min	0.02	0.06	0.02	0.02
			Max	0.63	0.39	0.26	0.16
			S.D.	0.17	0.09	0.08	0.10

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

Mooring Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Waquoit WAQ33	**8/15/2007**	**9/26/2007**	**42.2**	**89%**	**6%**	**0%**	**0%**	**0%**
Mean Chl Value = 6.8 ug/L			**Mean**	1.51	0.18	N/A	N/A	N/A
			Min	0.04	0.04	0.00	0.00	0.00
			Max	6.92	0.50	0.00	0.00	0.00
			S.D.	2.04	0.16	N/A	N/A	N/A
Waquoit WAQ24	**7/4/2007**	**7/26/2007**	**22.2**	**100%**	**83%**	**48%**	**18%**	**6%**
Mean Chl Value = 15.3 ug/L			**Mean**	22.08	0.71	0.28	0.17	0.13
			Min	22.08	0.04	0.04	0.04	0.04
			Max	22.08	2.88	0.96	0.58	0.29
			S.D.	N/A	0.82	0.25	0.14	0.10
Waquoit WAQ27	**7/3/2007**	**7/26/2007**	**22.6**	**56%**	**2%**	**0%**	**0%**	**0%**
Mean Chl Value = 5.4 ug/L			**Mean**	0.32	0.13	N/A	N/A	N/A
			Min	0.04	0.08	0.00	0.00	0.00
			Max	0.96	0.21	0.00	0.00	0.00
			S.D.	0.24	0.06	N/A	N/A	N/A

Generally, the dissolved oxygen records throughout the Eel Pond and Childs River sub-embayment to Waquoit Bay showed significant oxygen depletions during the critical summer period. The greatest oxygen depletions were generally associated with the upper reaches within Eel Pond and the main channel of the Childs River, while the basin of Eel Pond adjacent the tidal inlet showed only moderate levels of oxygen depletion, due to the direct influence of the high quality flood waters from Vineyard Sound. The D.O. records indicate that the upper reach of the Eel Pond and in the main channel of the Childs River show regular oxygen depletion (below 5.0 mg/L) during summer with frequent depletions below 4.0 mg/L and periodic depletions to less than 3 mg L^{-1}., consistent with nitrogen and organic matter rich waters (Table VII-1, Figure VII-3, VII-5 and Figure VII-7). The lower basin of Eel Pond located close to the inlet to Eel Pond showed a moderate level of oxygen depletion never declining below 4 mg L^{-1} and >5 mg L^{-1} for 94% of the 85 day record. The measured oxygen conditions were consistent with the general absence of macroalgae and moderate chlorophyll-*a* levels. However, it is virtually certain that the lower basin is strongly influenced by the nutrient and organic enriched low oxygen waters entering from the upper tidal reaches during out flowing ebb tides. The high turnover of water in the lower portion of Eel Pond reduces its ability to build up nutrients, phytoplankton biomass and organic matter. In addition, the inflow of high quality water from Vineyard Sound on the flooding tide, results in a lower basin with relatively high water quality for a portion of the flood tide period. The specific results of the DO/CHLA mooring program are as follows:

Waquoit Bay Main Basin – Upper WQA24 **(Figures VII-3 and VII-4):**
Oxygen conditions within the northern portion of the main basin of Waquoit Bay showed moderate levels of oxygen depletion consistent with the organically enriched sediments, moderate levels of phytoplankton biomass and generally low macroalgal accumulations associated with its observed level of nitrogen enrichment. Oxygen levels were generally greater than 5 mg L^{-1} (95% of record) and did not drop below 4 mg L^{-1}, although infrequent declines below 4 mg L^{-1} were observed in the water quality monitoring program. The time-series record of chlorophyll indicated moderate to high levels averaging 15.3 ug/L and frequently exceeding 20 ug/L (18% of 22 day record), however, the Mashpee Water Quality Program long-term record shows levels averaging 6.3 ug L-1 (2000-2010). Overall, the moderate levels of oxygen depletion and moderate chlorophyll-*a* levels with periodic large phytoplankton blooms, and generally low macroalgae accumulations within the northern basin are consistent with the generally productive benthic animal communities, comprised of transitional species (*Ampelisca*) that colonized its sediments.

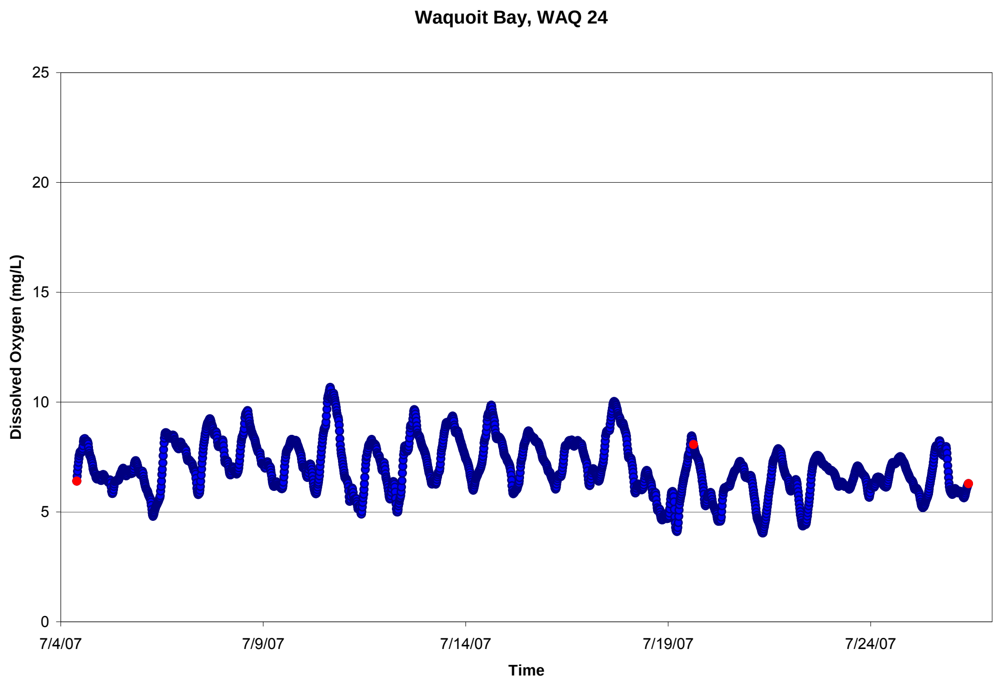


Figure VII-3. Bottom water record of dissolved oxygen at the northern mooring location in the upper tidal reach of the main basin of Waquoit Bay (WQA24), Summer 2007. Calibration samples represented as red dots.

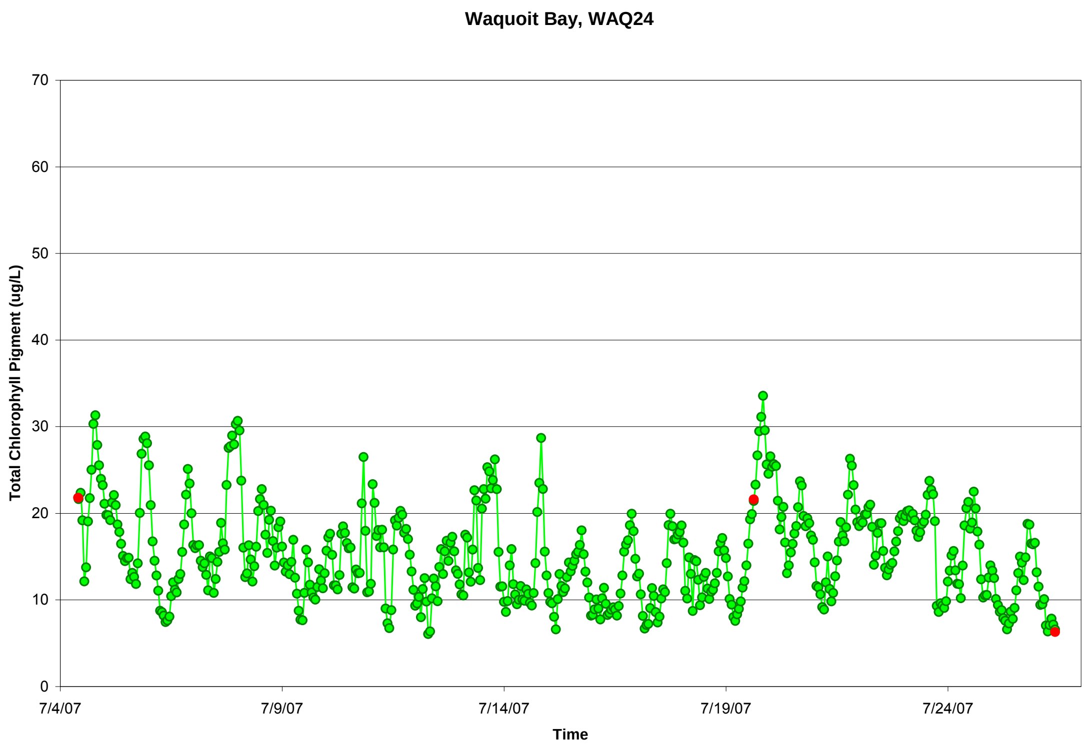


Figure VII-4. Bottom water record of Chlorophyll-*a* at the northern mooring location in the upper tidal reach of the main basin of Waquoit Bay (WQA24), Summer 2007. Calibration samples represented as red dots.

Waquoit Bay Main Basin – Middle WQA33 **(Figure VII-5 and Figure VII-6):**

A time-series bottom water D.O. and chlorophyll-*a* sensor was placed in the central region of the main basin of Waquoit Bay. The mooring was positioned in the middle portion of the main bay approximately 1.7 km to the north of the inlet which provides low nutrient waters from Vineyard Sound. Large daily excursions in oxygen levels (5-7 mg L^{-1}) were observed at this location, ranging from levels at or well above air equilibration to stressful oxygen conditions where levels frequently decline to 3 mg L^{-1} and lower (Figure VII-5, Table VII-1). Large daily excursions in oxygen levels is a clear indication organic enrichment resulting from nitrogen loading and within the main basin manifests itself through organic enrichment of sediments, large macroalgal accumulations and phytoplankton biomass. The effects of these parameters is to unbalance the water column oxygen cycle, through high rates of oxygen input through photosynthesis in daylight and high rates oxygen uptake during darkness. The result is oxygen levels above air equilibration in daytime and low oxygen levels at night. While it is not possible to partition the role of phytoplankton versus macroalgae in determining the oxygen balance in the mid basin, it should be noted that very large quantities of macroalgae were observed throughout this basin. MEP divers observed extensive accumulations with 100% coverage of the bottom approximately 20-30 cm thick. Clearly this played a role in the very high daytime oxygen levels which regularly persisted over 10 mg L^{-1} and occasionally exceeded 20 mg L^{-1}. In contrast, night time oxygen levels declined below 4 and 3 mg L^{-1} approximately 11% and 5% of the 42 days of mooring deployment, with infrequent depletions to less than 1 mg L^{-1}. Over the 42 day deployment there does not appear to be any significant distinct bloom of phytoplankton beyond a relatively moderate base level that is maintained through the entire deployment period (7 ug L^{-1}). During the mooring deployment, chlorophyll-*a* values generally ranged between 5 and 10 ug L^{-1}. Oxygen levels at this location in the middle portion of the main bay are clearly indicative of impaired conditions and nitrogen enrichment due to the extensive macroalgal cover with additional contribution by the moderate sustained phytoplankton biomass. Chlorophyll-*a* levels exceeded the 5 and 10 ug L^{-1} benchmarks 89% and 6% of the time respectively (Table VII-2, Figure VII-6). Average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments (Cooksey et. al., 2010).

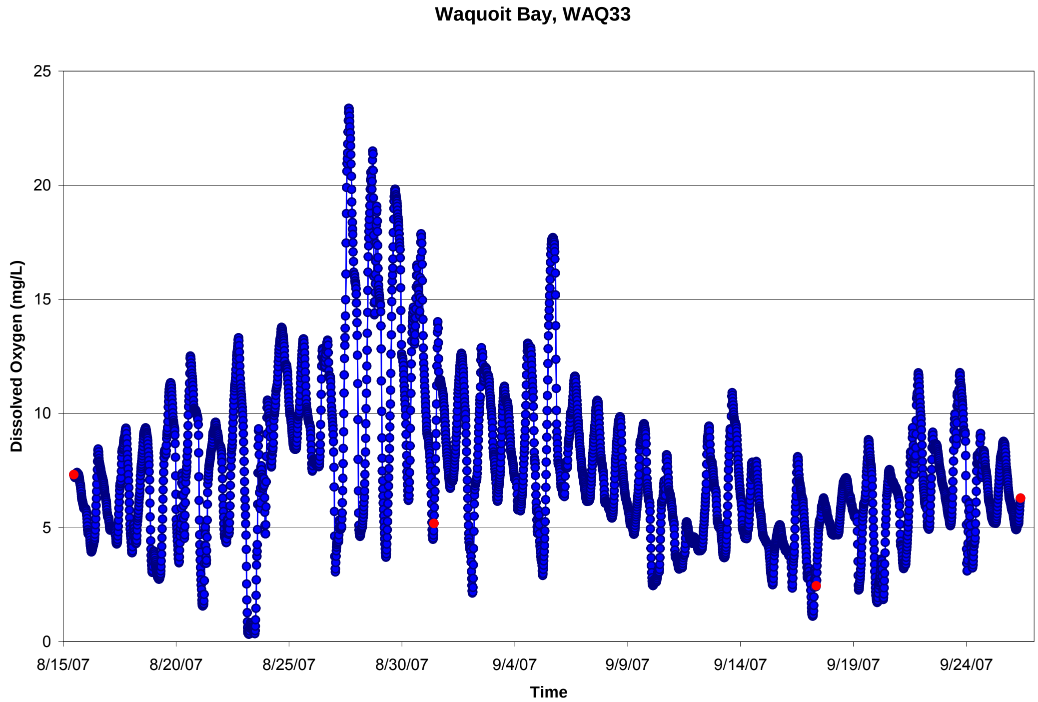


Figure VII-5. Bottom water record of dissolved oxygen within the mid region of the main basin of Waquoit Bay (WQA33), Summer 2007. Calibration samples represented as red dots.

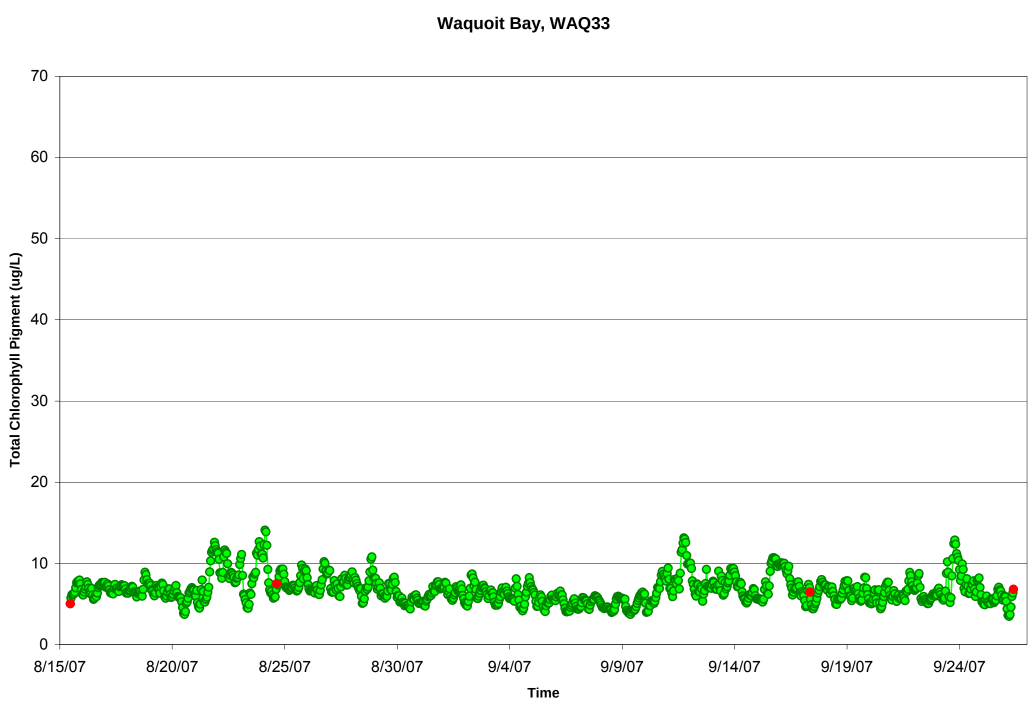


Figure VII-6. Bottom water record of Chlorophyll-*a* within the mid region of the main basin of Waquoit Bay (WQA33), Summer 2007. Calibration samples represented as red dots.

Waquoit Bay Main Basin – Lower WQA27 **(Figures VII-7 and VII-8):**

To capture the full gradient in oxygen levels across the main basin of Waquoit Bay, a third time-series sensor was placed in the lower portion of the main bay approximately 700 meters to the east of the tidal inlet which provides low nutrient high quality waters from Vineyard Sound on flooding tides. Large daily excursions in oxygen levels were observed at this location, less than observed in the mid reach and similar to the upper most reach. Diurnal oxygen excursions ranged from levels at or above air equilibration to less than 5 mg L^{-1} (Figure VII-7, Table VII-1). It should be noted that similar to the middle of the main basin, daily oxygen excursions at this location are likely driven by both the accumulations of macroalgae and enhanced phytoplankton biomass. Generally oxygen levels within the lower reach of the main basin were only moderately depleted. Oxygen levels regularly persisted between 7-8 mg L^{-1} and occasionally exceeded 10 mg L^{-1} and declined below 5 mg L-1 for 15% and to less than 4 mg L^{-1} for ~3% of the 23 day record, while the water quality monitoring program has observed only levels > 5 mg L^{-1}. Over the 23 day deployment there does not appear to be any significant rise in the level of phytoplankton beyond a low to moderate base level that is maintained through the entire deployment period. During the mooring deployment, chlorophyll-*a* values ranged narrowly from between 5 and 10 ug L^{-1}. Chlorophyll values were moderate (mooring chlorophyll average 5.4 ug L^{-1}) and chlorophyll-*a* levels exceeded the 5 and 10 ug L^{-1} benchmarks 56% and 2% of the time respectively (Table VII-2, Figure VII-8). Average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments. Oxygen levels at this location in the lower portion of the main bay show only low to moderate impairment associated with nitrogen enrichment, although these conditions coupled with the macroalgal accumulations have been sufficient to result in the loss of eelgrass coverage throughout almost all of the lower reach of the main basin. It should be noted that conditions at this "inlet" location are the highest quality within the main basin of Waquoit Bay.

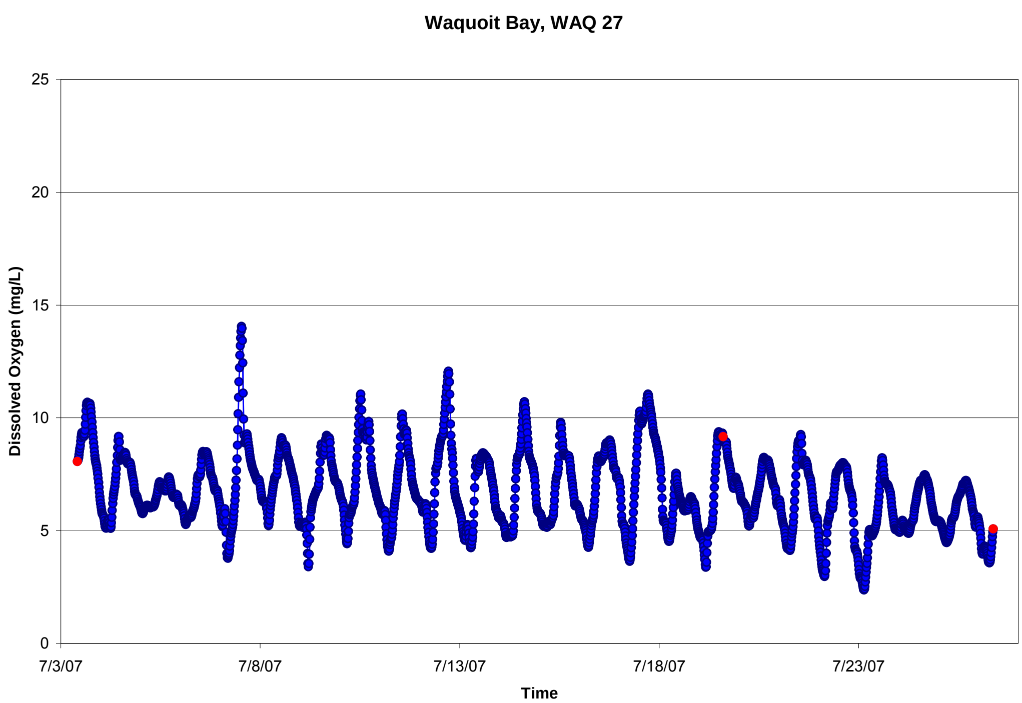


Figure VII-7. Bottom water record of dissolved oxygen within the lower region of the main basin of Waquoit Bay (WQA27), Summer 2007. Calibration samples represented as red dots.

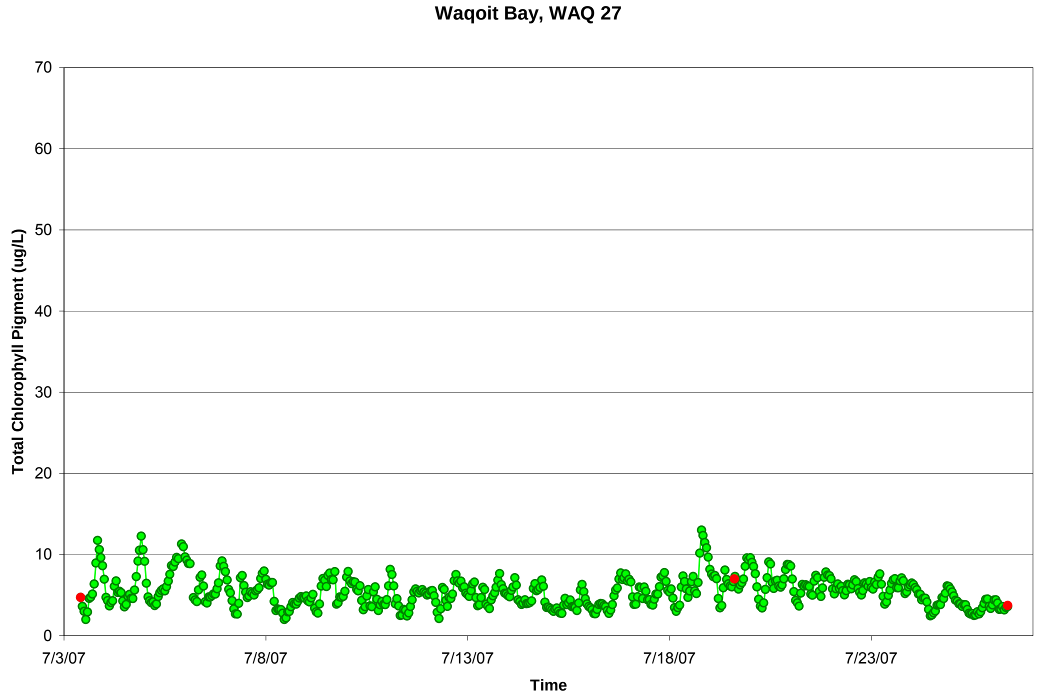


Figure VII-8. Bottom water record of Chlorophyll-*a* within the lower region of the main basin of Waquoit Bay (WQA27), Summer 2007. Calibration samples represented as red dots.

VII.2.2 Bottom water Dissolved Oxygen Results for eastern sub-embayments (Quashnet River, Hamblin Pond, Jehu Pond)

Similar to other embayments in southeastern Massachusetts, the eastern sub-embayments to the overall Waquoit Bay System 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. This phenomenon is best seen in the Quashnet River record, where dissolved oxygen levels frequently drop to less than 4 mg L^{-1} during the night and reach levels in excess of atmospheric saturation during the day time (Figure VII-9). 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. More important, both the level of oxygen depletion and the magnitude of daily oxygen excursion indicate nutrient enriched waters and impaired habitat quality at both mooring sites (Quashnet River, Figure VII-9 and Hamblin Pond, Figure VII-10). The dissolved oxygen records for the tidally influenced lower Quashnet River and the upper region of Hamblin Pond indicate that these sub-embayments currently maintain a high and moderate level of oxygen stress, respectively. Jehu Pond showed a high level of oxygen depletion, at a level which will impair habitat quality, with dissolved oxygen levels periodically approaching anoxia.

Dissolved oxygen records were analyzed to determine the percent of the deployment time (29-37 days) that oxygen was below various benchmark concentrations (Table VII-3). The data collected by the water quality monitoring programs for Jehu Pond was of sufficient size to allow a frequency analysis similar to that for the moored instruments in Quashnet River and Hamblin Pond. These data indicate not just the minimum or maximum levels of this critical nutrient related constituent, but the intensity of the low oxygen circumstances. 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. From the oxygen records it is clear that, after Jehu Pond, the Quashnet River has the greatest extent of oxygen depletion and the oxygen excursion indicates a high degree of nutrient enrichment (as is supported by the chlorophyll-*a* data, as described later in this Section). Note that this data are from the lower part of this system, which has the highest water quality, but still the oxygen levels are <4 mg L^{-1} almost 10% of the time. However, use of only the duration of oxygen below for example 4 mg/L^{-1} would underestimate oxygen stress in this system. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae), oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems. The Quashnet River data indicates that daily excursions of 15 mg L^{-1} in bottom water oxygen do occur. This is the case in the Quashnet River and to a lesser extent in Hamblin Pond.

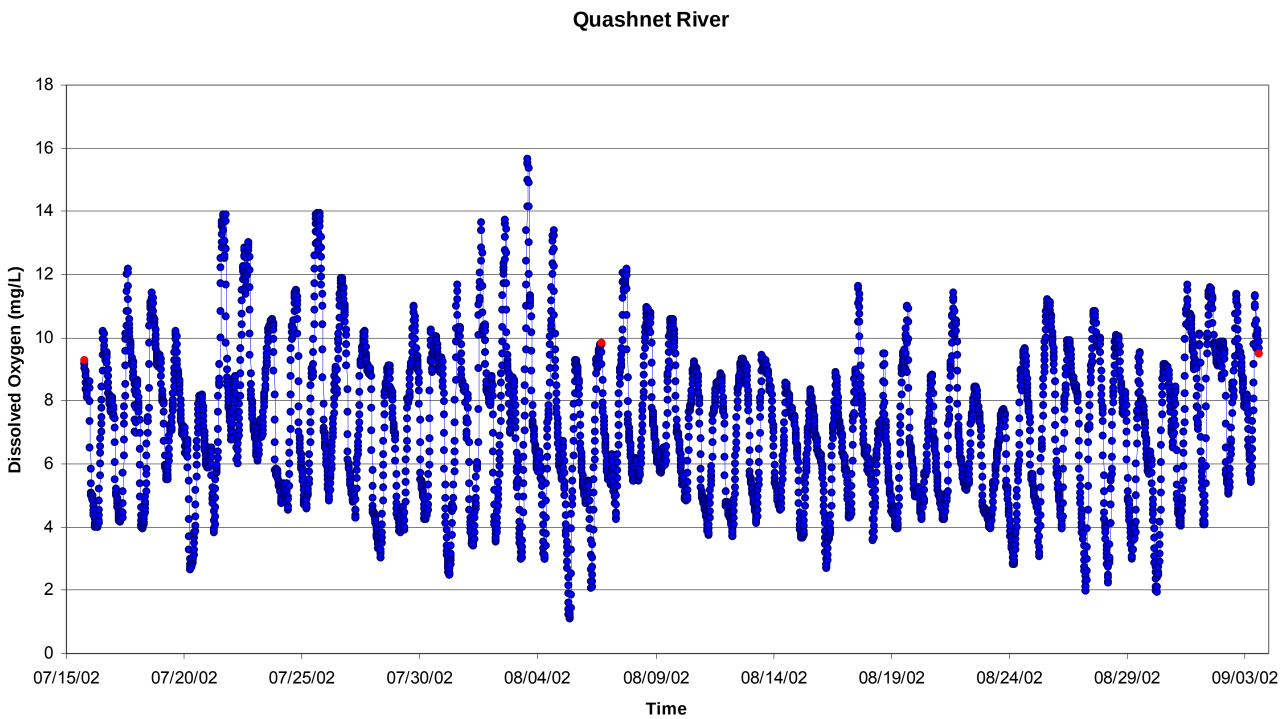


Figure VII-9. Bottom water record of dissolved oxygen (top panel) in the Quashnet River Estuary (lower basin), summer 2002. Calibration samples represented as red dots.

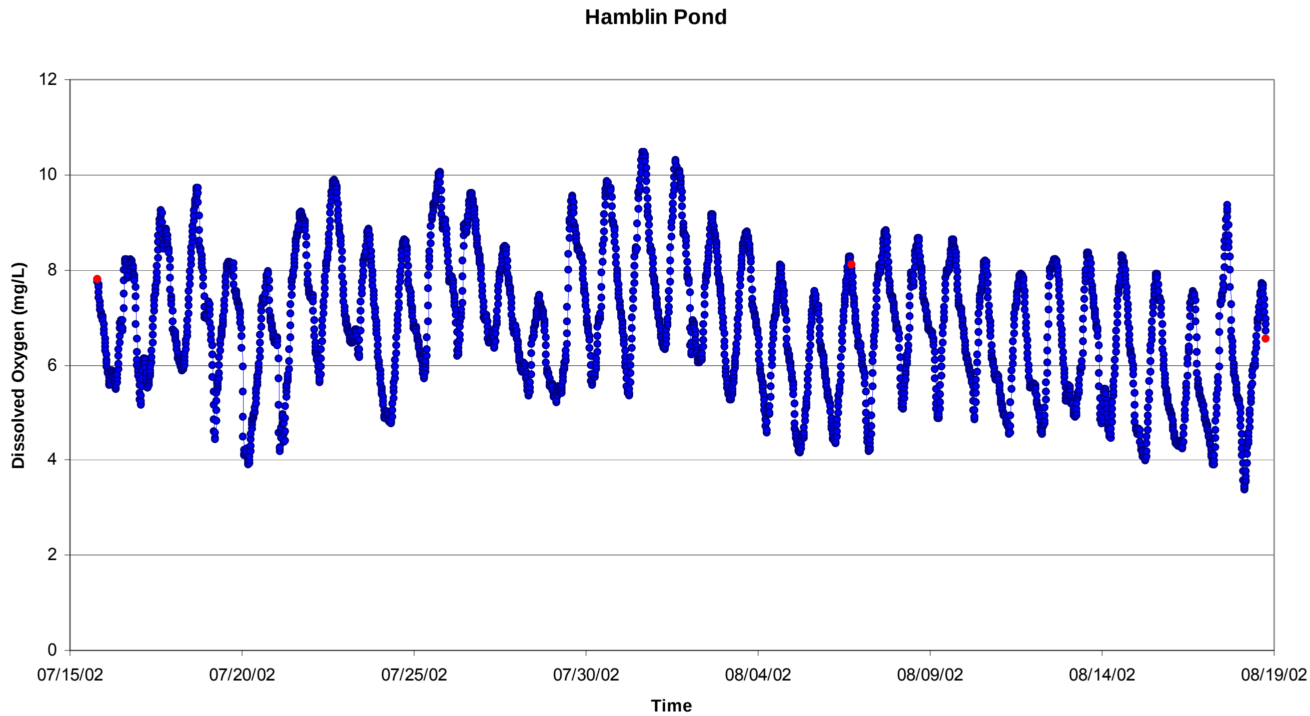


Figure VII-10. Bottom water record of dissolved oxygen (bottom panel) in Hamblin Pond, summer 2002. Calibration samples represented as red dots.

Table VII-3. Percent of time during deployment of *in situ* sensors or of traditional grab sampling events that bottom water oxygen levels were below various benchmark oxygen levels.

Massachusetts Estuaries Project Town of Mashpee: 2002					
	Dissolved Oxygen: Summer				
Waquoit Bay Sub-Embayments	**Total Days**	**<6 mg/L (% of days)**	**<5 mg/L (% of days)**	**<4 mg/L (% of days)**	**<3 mg/L (% of days)**
Continuous Record: 2002					
Hamblin Pond	29	31%	11%	1%	0%
Quashnet River (lower)	37	36%	21%	8%	2%
Grab Samples 1994-2003+					
Jehu Pond	43	81%	65%	37%	14%
Quashnet River (mid)	68	66%	46%	28%	13%

+ **Composite of Mashpee/SMAST and WBNERR (from NERR Web Site) grab sampling data; days = Number of sampling dates.**

Chlorophyll-*a* data for each of the three estuaries collected by the water quality monitoring program was of sufficient size to allow a frequency analysis similar to that for dissolved oxygen (Table VII-4). The difference between the chlorophyll levels assayed by the Baywatch Program and Mashpee Program cannot be definitively explained. However, some difference was expected as the Mashpee Program assays for total chlorophyll-*a* pigment (sum of chlorophyll-*a* and its immediate breakdown product, pheophythin a) which is a better indicator of bloom conditions. The Mashpee/SMAST data were used for this MEP analysis, but the Baywatch data are presented for comparison, as it is a longer dataset. Both data sets show similar patterns of nitrogen related habitat quality. It is clear that the Quashnet River is highly eutrophic with total chlorophyll-*a* levels in the upper and mid regions averaging >20 ug L^{-1} (SMAST data presented in Figure VII-11). The moored chlorophyll sensor showed similarly high values (Table VII-5). Phytoplankton blooms appear to be generated within the upper and mid basins of the Quashnet, most likely as a result of the high nitrogen loading to the headwaters via the Quashnet River freshwater discharge. It is interesting that on three sampling events the upper station showed exceedingly large blooms (>140 ug L^{-1}), while on three separate events the mid station showed very large blooms (>40 ug L^{-1}). The pattern seems to indicate potentially separate points of origination (upper versus mid), although a flushing out of an upper bloom cannot be discounted in the observed mid bloom events.

Jehu and Hamblin Ponds support lower total chlorophyll levels, averaging 11.9 and 7.4 µg L^{-1}, respectively. Jehu Pond appears to be showing more nutrient enrichment than Hamblin Pond both on average and in the size of the blooms (Table VII-4, maximum values). The high phytoplankton biomass in Jehu Pond is consistent with the observation of oxygen stress in this system. The moderate total chlorophyll levels in Hamblin Pond are consistent with its moderately good oxygen status. The agreement between the chlorophyll and oxygen levels in these Pond basins is likely the result of their physical structure. At first glance the Quashnet River did not show the same relationship. However, this likely results in part from the placement of the oxygen mooring in the lower basin which supports lower phytoplankton levels than the mid and upper stations above the bridge (Figure VII-12). However, traditional “grab” sampling data are also available for the mid station. These data indicate a high degree of oxygen depletion with almost one third of the sampling dates showing oxygen levels <4 mg L^{-1}. This pattern is also seen in the limited oxygen data from the upper region of this system. Taken in whole, it appears that the Quashnet River Estuary is showing oxygen stress throughout its reach and it is likely that the level of depletion is higher in the upper and mid reaches than in the lower basin, consistent with the distribution of phytoplankton biomass.

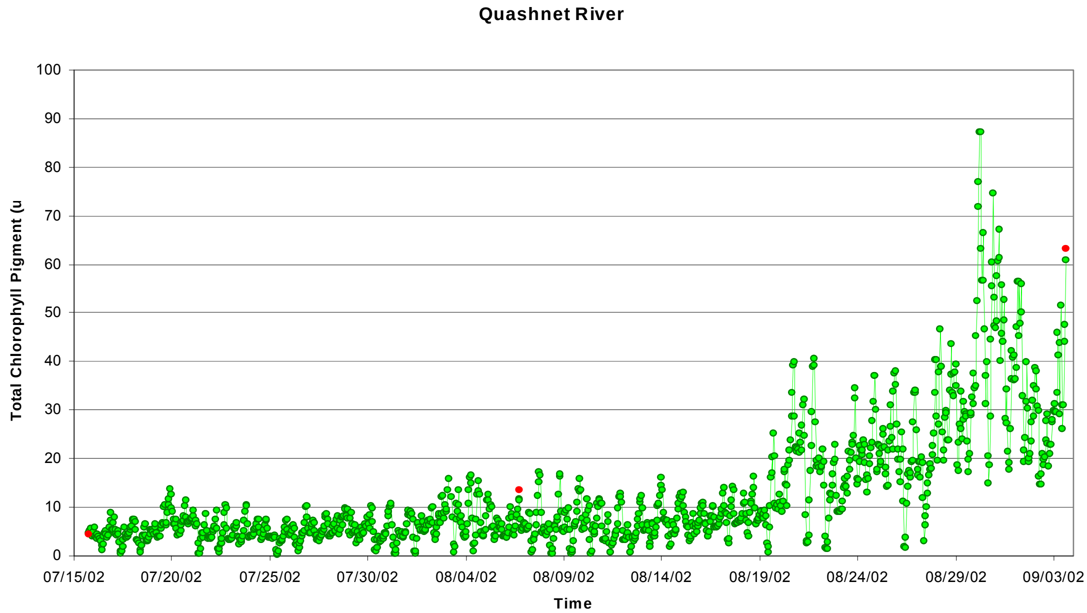


Figure VII-11. Bottom water record of chlorophyll-*a* (bottom panel) in the Quashnet River Estuary (lower basin), summer 2002. Calibration samples represented as red dots

Combining the dissolved oxygen and chlorophyll-*a* data yield a clear pattern of nutrient related habitat quality. A further analysis incorporating eelgrass and infaunal indicators is included later in this Section. At present, the Quashnet River estuary is showing poor oxygen status (based upon depletions, daily excursions, mooring in lower basin) and large phytoplankton blooms. While this system appears to be stressed throughout, there is a clear gradient from hypereutrophic in the upper regions to eutrophic in the lower basin. Jehu Pond is also showing nitrogen enriched conditions, with periodic hypoxia/anoxia in the basin and high phytoplankton biomass. Hamblin Pond is showing the best nutrient related habitat quality, based both upon its moderately good oxygen conditions and moderate phytoplankton biomass. Based upon the dissolved oxygen and chlorophyll data the nutrient related habitat quality of the three estuarine sub-embayments to eastern Waquoit Bay can be classified is as follows:

- Quashnet River estuary – Significantly Impaired
- Jehu Pond – Moderately/Significantly Impaired
- Hamblin Pond – Moderately Impaired

Table VII-4. Levels of chlorophyll-*a* pigments within the Town of Mashpee sub-embayments to Waquoit Bay. All data were collected by grab samples from June-September. Data collected by the Waquoit Bay BayWatcher Program (WBNERR) and by Popponesset Bay Water Quality Monitoring Program and Coastal Systems Program, SMAST (SMAST). Geometric averages were used to estimate "average" conditions, given the periodic phytoplankton blooms. WBNERR data (June-September) is from the BayWatcher samplings garnered from NERR Web site.

	Sampling			**Statistics**				
	Source	**Station**	**Year**	**Geo Mean ug/L**	**Geo Stdev ug/L**	**Max ug/L**	**Min ug/L**	**N**
Waquoit Bay Sub-Embayments								
Hamblin Pond								
Mid	WBNERR	Site 3	1998-2002	2.1	2.6	9.5	0.2	29
Mid	SMAST	WB-4	2001-2003	7.4	1.7	28.3	3.2	12
Jehu Pond								
Mid	WBNERR	Site 4	1998-2002	2.8	2.1	9.2	0.7	25
Mid	SMAST	WB-1	2001-2003	11.9	2.0	47.1	4.2	12
Quashnet River								
Upper	WBNERR	--	--	--	--	--	--	--
Upper	SMAST	WB-07	2001-2003	22.7	4.1	168.8	2.7	11
Mid	WBNERR	Site 5	1998-2002	4.6	3.6	80.2	0.6	34
Mid	SMAST	WB-08	2001-2003	20.1	2.1	53.2	5.5	11
Lower	WBNERR	--	--	--	--	--	--	--
Lower	SMAST	WB-09	2001-2003	9.7	2.0	44.5	4.8	12

Table VII-5. Frequency (number of events during deployment) and duration (total number of days over deployment) of chlorophyll-*a* levels above various benchmark levels from MEP continuous records from Hamblin Pond and Quashnet River.

	Start Date	End Date	Total Deployment (Days)	Duration (cumulative days) >5 ug/L (Days)	>10 ug/L (Days)	>15 ug/L (Days)	>20 ug/L (Days)	>25 ug/L (Days)	Frequency (# events) >5 ug/L (#)	>10 ug/L (#)	>15 ug/L (#)	>20 ug/L (#)	>25 ug/L (#)
Waquoit Bay Sub-Embayments													
Hamblin Pond	15-July 2002	18-Aug 2002	34.0	**Sensor Failure**									
			Mean										
			Min										
			Max										
			S.D.										
Quashnet River	15-July 2002	3-Sept 2002	49.8	35.17	18.17	12.92	9.38	6.63	76	45	22	30	25
			Mean	0.46	0.40	0.59	0.31	0.27					
			Min	0.04	0.04	0.04	0.04	0.04					
			Max	7.25	7.17	3.04	0.96	0.92					
			S.D.	0.94	1.14	0.81	0.30	0.26					

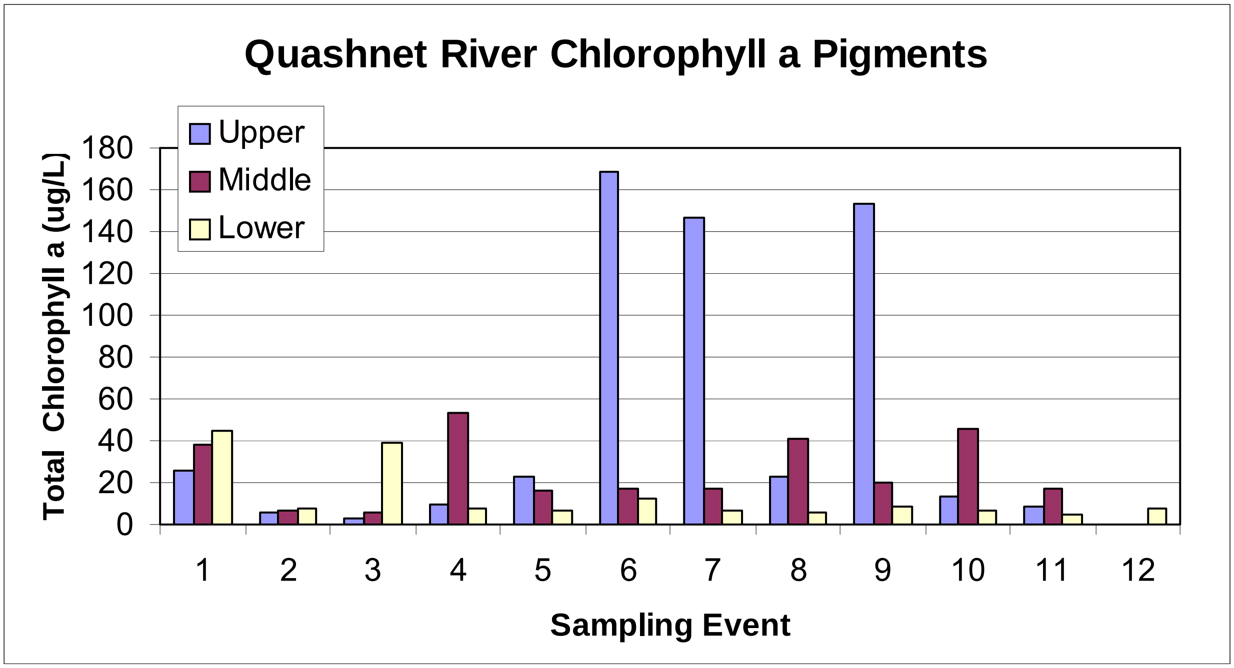


Figure VII-12. Distribution of chlorophyll-*a* pigments within the Quashnet River Estuary from grab sampling by the Mashpee Water Quality Monitoring Program-Coastal Systems Program (SMAST) 2001 - 2003.

VII.2.3 Bottom water Dissolved Oxygen Results for Western Sub-embayments (Eel Pond, Childs River)

To assess oxygen and chlorophyll-*a* levels within the western sub-embayments to the Waquoit Bay System for comparison to the other portions of the System and other estuaries throughout the region, time-series measurements were collected using sensor deployed within the upper reach of Eel Pond, the lower main basin and the main channel of the Childs River. Both dissolved oxygen and chlorophyll-*a* showed high frequency variation related primarily to diurnal and sometimes tidal influences. The magnitude of the daily excursions as well as the extent of oxygen depletion again was significantly different between the sites, primarily due to their level of nitrogen enrichment, with the upper reaches showing greater oxygen excursions and oxygen depletion than the lower basin of Eel Pond.

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 23-85 day deployment period that these parameters were below or above various benchmark concentrations (Tables VII-6, VII-7). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

Table VII-6. Duration (percent of deployment time) that bottom water dissolved oxygen levels were below various benchmark levels within the Eel Pond and Childs River portions of the overall Waquoit Bay system. "Mean" represents the average duration of each event over the benchmark level and "S.D." its standard deviation. Data collected by the Coastal Systems Program, SMAST.

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Waquoit WAQ8	**7/3/2007**	**9/26/2007**	**84.9**	**38.30**	**5.26**	**0.00**	**0.00**
			Mean	0.60	0.22	N/A	N/A
			Min	0.01	0.03	0.00	0.00
			Max	5.96	0.71	0.00	0.00
			S.D.	1.07	0.19	N/A	N/A
Waquoit WAQ12	**7/13/2007**	**9/26/2007**	**22.9**	**12.36**	**8.77**	**5.58**	**2.46**
			Mean	0.26	0.15	0.11	0.06
			Min	0.01	0.01	0.01	0.01
			Max	1.21	0.54	0.38	0.19
			S.D.	0.25	0.14	0.09	0.05
Waquoit Eel River	**7/13/2007**	**9/26/2007**	**74.9**	**44.31**	**30.79**	**16.45**	**4.93**
			Mean	0.60	0.35	0.20	0.13
			Min	0.03	0.01	0.01	0.01
			Max	2.68	1.63	1.25	0.51
			S.D.	0.43	0.25	0.19	0.13

Table VII-7. Duration (% of deployment time) that chlorophyll-*a* levels exceed various benchmark levels within the Eel Pond and Childs River portions of the overall Waquoit Bay embayment system. “Mean” represents the average duration of each event over the benchmark level and “S.D.” its standard deviation. Data collected by the Coastal Systems Program, SMAST.

Mooring Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Waquoit WAQ8	**7/3/2007**	**9/26/2007**	**85.2**	**59%**	**18%**	**2%**	**0%**	**0%**
Mean Chl Value = 6.2 ug/L			**Mean**	1.02	0.28	0.11	0.06	N/A
			Min	0.04	0.04	0.04	0.04	0.00
			Max	19.21	3.08	0.38	0.08	0.00
			S.D.	2.86	0.44	0.09	0.02	N/A
Waquoit WAQ12	**7/3/2007**	**7/26/2007**	**22.9**	**100%**	**94%**	**76%**	**53%**	**37%**
Mean Chl Value = 23.3 ug/L			**Mean**	22.92	1.80	0.64	0.28	0.23
			Min	22.92	0.04	0.08	0.04	0.04
			Max	22.92	7.33	3.75	0.92	0.88
			S.D.	#DIV/0!	2.55	0.85	0.23	0.21
Waquoit Eel River	**7/3/2007**	**7/26/2007**	**72.0**	**94%**	**67%**	**46%**	**34%**	**23%**
Mean Chl Value = 17.4 ug/L			**Mean**	3.09	0.76	0.71	0.37	0.28
			Min	0.04	0.04	0.04	0.04	0.04
			Max	43.38	17.08	9.13	3.00	2.88
			S.D.	9.12	2.57	1.74	0.51	0.41

Generally, the dissolved oxygen records within the Eel Pond and Childs River sub-embayments to Waquoit Bay showed significant oxygen depletions during the critical summer period. The greatest oxygen depletions were generally associated with the mooring locations situated furthest away from the inlet to Eel Pond with higher oxygen levels maintained in the basin closest to the inlet where the Childs River meets with Eel Pond. The continuous D.O. records indicate that the upper reaches of the Eel Pond and Childs River sub-embayments show regular oxygen depletion below 5.0 mg L^{-1} during summer months with periodic depletions below 4.0 mg L^{-1} and 3.0 mg L^{-1}, consistent with the lower flushing and focus of watershed nitrogen inputs on the upper reaches of these sub-embayments that results in the nitrogen and organic matter enrichment of their waters (Table VI-1,Table VII-6, Figure VII-13, VII-15 and Figure VII-17). Within the lower basin of Eel Pond (site WQA8), situated close to the tidal inlet, bottom water was also depleted but to a much lesser extent then in the upper tidal reaches of the western basins. Although oxygen did periodically drop below 5 mg L^{-1} (6% of 85 day record) it did not fall below 4 mg L^{-1} and showed only moderate levels of chlorophyll-*a*. However, it is virtually certain that the water quality within this lower basin is significantly affected by the water quality within the upper reaches of the western basins, as ebbing waters transport high nutrient, high phytoplankton, low oxygen waters through the lower basin to Vineyard Sound on the ebb tide. The inflow of high quality water from Vineyard Sound on the flooding tide, results in a lower basin with relatively high water quality for a portion of the flood tide period. The specific results of the time-series oxygen and chlorophyll-*a* measurements are as follows:

***Eel Pond, West Branch – Upper Reach* (Figures VII-13 and VII-14):**

The upper reach of the west branch of Eel Pond mooring site was centrally located within the upper third of the basin immediately down gradient from the confluence of the two tributaries that form the most inland extent of the basin (Figure VII-2). There were large daily excursions in oxygen levels, ranging from levels in excess of air equilibration to less than 3 mg L-1 (Figure VII-13, Table VII-6). Oxygen levels frequently were less than 4 mg L^{-1} and periodically less than 3 mg L^{-1}, approximately 22% and 7% of the 75 days of mooring deployment, respectively. The consequences of nitrogen enrichment within this upper reach of Eel Pond is manifest in the large and prolonged sequence of phytoplankton blooms observed through July and August. Oxygen varied primarily with light (diurnal cycle) and to a lesser extent with tides. Lowest oxygen levels were generally observed in the early morning. Highest dissolved oxygen was observed when low tide occurred at the end of the photocycle (ca. 1500 hrs). Equally indicative of eutrophic conditions, oxygen levels often exceeded 8 mg L^{-1} and occasionally reached above 10 and 11 mg L^{-1}, consistent with the high phytoplankton biomass. Consistent with the oxygen levels, chlorophyll-*a* was very high over the entire study period. The large phytoplankton blooms in July and August supported chlorophyll-*a* levels of over 20 ug L^{-1} (34% of record) and were 40 ug L^{-1} to over 50 ug L^{-1} for about a month. Even after the blooms declined, chlorophyll-*a* levels remained relatively high at ~10 ug L^{-1}. Oxygen and chlorophyll levels within the upper reach of the west branch of Eel Pond are clearly indicative of impaired conditions consistent with nitrogen enrichment. Average chlorophyll-*a* was 17.4 ug, consistent with the Mashpee Water Quality Monitoring Program average of ~20 ug L-1 over the mid to upper basin and chlorophyll-*a* levels exceeded the 10 and 20 ug L^{-1} benchmarks 67% and 34% of the time respectively (Table VII-7, Figure VII-14). Average chlorophyll levels over 10 ug L^{-1} have been used to indicate eutrophic conditions in embayments (Cooksey et. al., 2010).

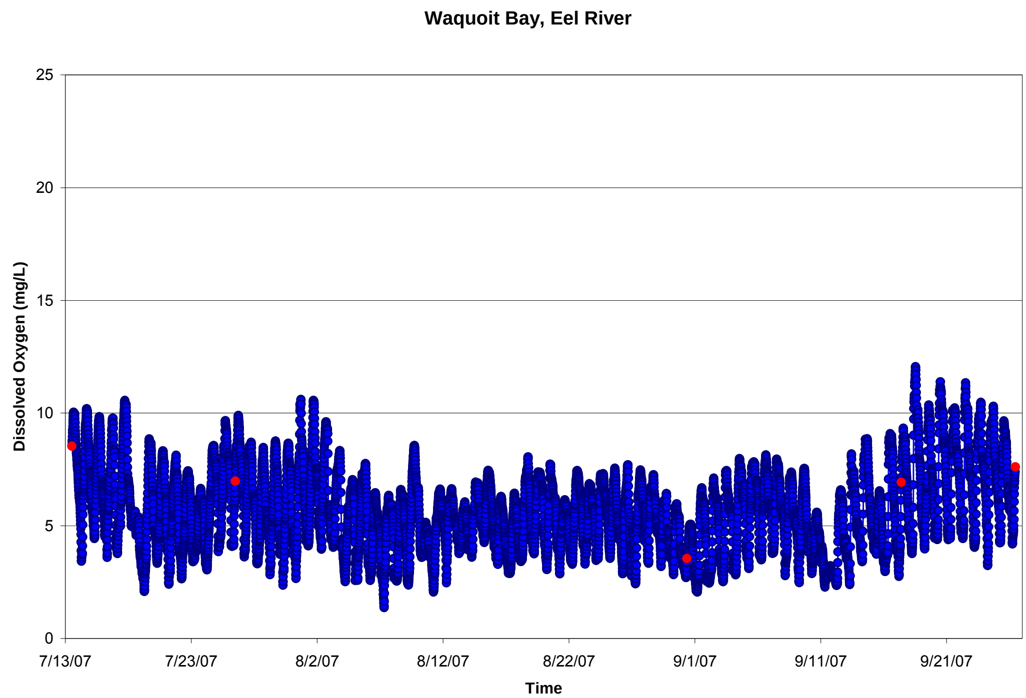


Figure VII-13. Bottom water record of dissolved oxygen within the upper reach of the west branch of the Eel Pond sub-embayment to Waquoit Bay, Summer 2007. Calibration samples represented as red dots.

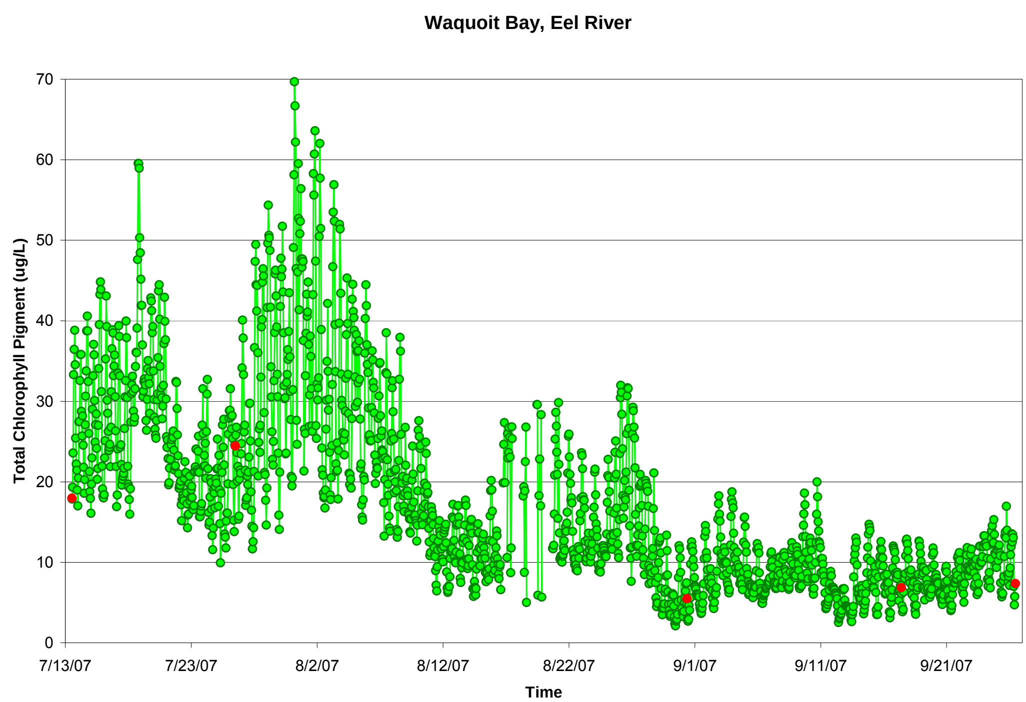


Figure VII-14. Bottom water record of Chlorophyll-*a* within the upper reach of the west branch of the Eel Pond sub-embayment to Waquoit Bay, Summer 2007. Calibration samples represented as red dots.

Eel Pond – Lower WQA8 **(Figure VII-15 and Figure VII-16):**

Oxygen and chlorophyll-*a* levels within the lower basin of Eel Pond were monitored over the summer (85 days) using continuously recording sensors (mooring WQA8) located within the lower basin of the Eel Pond to the east of the where the east and west branches come together. The mooring was to the east of the tidal inlet positioned so as to not be immediately influenced by the inflowing waters from Vineyard Sound (Figure VII-2). In contrast to the upper reach of Eel Pond, oxygen conditions within the lower basin showed only modest daily excursions and generally daily oxygen minima. Oxygen did not usually exceed air equilibration (7-8 mg L^{-1}) and while oxygen depletion was observed, levels were generally above 5 mg L-1 94% of record and remained above 4 mg L-1 throughout the 85 day record (Figure VII-15, Table VII-6). Similarly the Mashpee Water Quality Monitoring Program found oxygen levels to be >5 mg L-1 91% and between 4-5 mg L-1 on only 9% of their 34 days of sampling (2005-2010). The low organic enrichment of this lower portion of the Eel Pond sub-embayment is seen in the much lower chlorophyll-*a* levels and smaller bloom compared to the upper basin (Figures VIII-16, VIII-14). Oxygen varied primarily with light (diurnal cycle) and to a lesser extent with tides. Lowest oxygen (which seldom dropped below 5 mg L^{-1}) was generally observed in the early morning. Highest dissolved oxygen was observed when low tide occurred at the end of the photocycle (ca. 1500 hrs). In general, the pattern of oxygen concentrations is consistent with the low to moderate phytoplankton biomass, as measured by chlorophyll-*a*, and low macroalgal accumulations within this basin. Over the 75 day deployment the small bloom that occurred in the middle of the deployment did reach levels of between 10 ug L^{-1} and 20 ug L^{-1} for approximately a 2 week period, but average chlorophyll was low to moderate, 6.2 ug L^{-1} over the record. During the latter part of the deployment chlorophyll concentrations declined to low levels, 2-3 ug L^{-1}, a relatively low base level of phytoplankton for summer time conditions. Oxygen and chlorophyll levels at this location in the lower basin of Eel Pond are clearly indicative of a low level of impairment and low nitrogen enrichment, although chlorophyll-*a* levels exceeded the 10 and 15 ug L^{-1} benchmarks 18% and 2% of the time respectively (Table VII-7, Figure VII-16). Average chlorophyll levels over 10 ug L^{-1} have been used to indicate eutrophic conditions in embayments (Cooksey et. al., 2010).

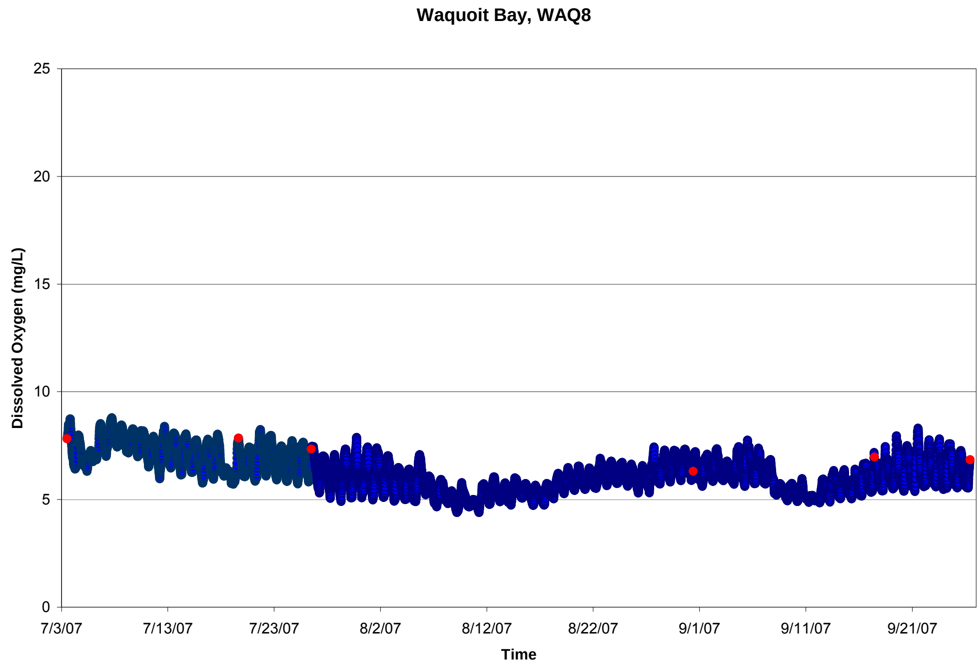


Figure VII-15. Bottom water record of dissolved oxygen within the main lower basin of Eel Pond, mooring location WAQ-8, Summer 2007. Calibration samples represented as red dots.

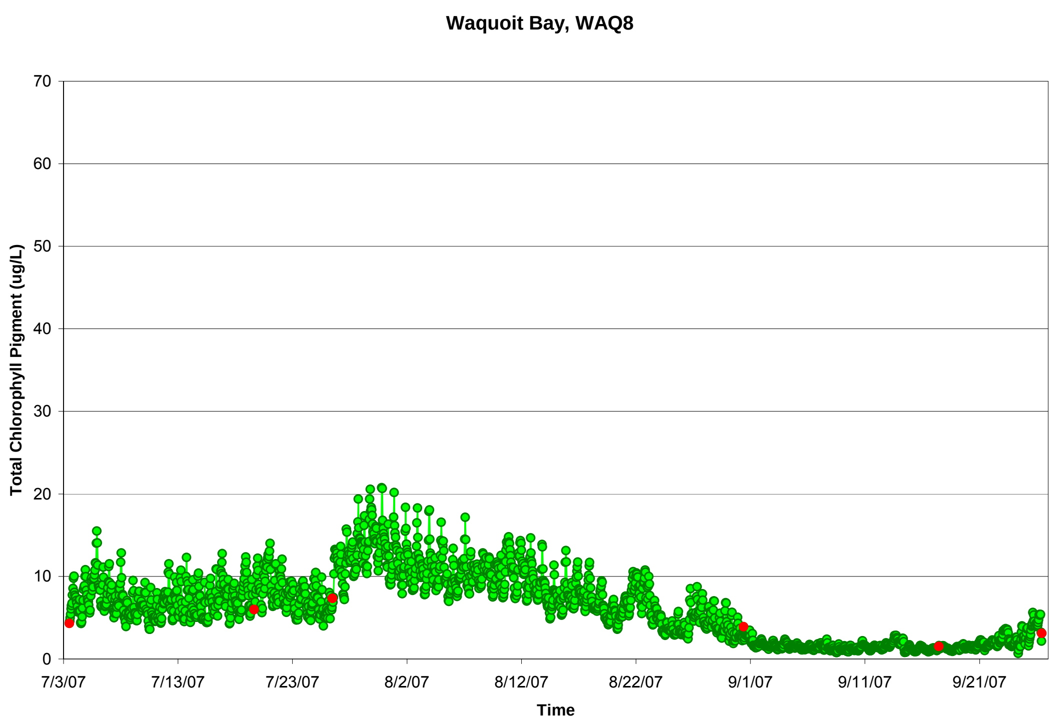


Figure VII-16. Bottom water record of Chlorophyll-*a* within the main lower basin of Eel Pond, mooring location WAQ-8, Summer 2007. Calibration samples represented as red dots.

***Childs River – WQA12* (Figures VII-17 and VII-18):**

The main channel of the Childs River showed large oxygen excursions, significant oxygen depletions and high chlorophyll-*a* levels throughout the 23 day record (mooring WQA12). The mooring was located approximately 1 km south of the Route 28 bridge (Figure VII-2). There were very significant daily excursions in oxygen levels throughout the record, ranging from levels well in excess of air equilibration to frequent declines below 3 mg L^{-1} (Figure VII-17, Table VII-6). Oxygen levels were measured below 4 and 3 mg L^{-1} approximately 24% and 11% of the 23 day deployment, respectively. The organic enrichment of the Childs River sub-embayment is clear from the high chlorophyll-*a* level observed throughout the deployment period, average of 23.3 ug L^{-1}, as well as dense patches of accumulated drift macroalgae. Oxygen varied primarily with light (diurnal cycle) and to a lesser extent with tides. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed when low tide occurred at the end of the photocycle (ca. 1500 hrs). Consistent with significant nitrogen and organic enrichment, there were large diurnal excursions in bottom water oxygen concentration, frequently more than 10 mg L^{-1} on a single day, with maxima well above atmospheric equilibration, frequently 10 and 15 mg L^{-1} (2 times equilibration). These large excursions coupled with the very high maxima strongly indicate a system impaired by nitrogen enrichment. The integrated effects of the high chlorophyll-*a* levels and accumulations of drift macroalgae and organic enrichment of the sediments result in high day time oxygen levels that rapidly decline to levels stressful to estuarine organisms due to dark respiration. This is clearly a sign of an oxygen cycle that is out of balance. consistent with the oxygen levels, chlorophyll-*a* was very high over the entire study period (averaging 23.3 ug L^{-1}), rarely dropping below 10 ug L^{-1} and generally between 15 and 40 ug L^{-1}. Chlorophyll-*a* levels exceeded the 10 and 20 ug L^{-1} benchmarks 94% and 53% of the time respectively (Table VII-7, Figure VII-18). Average chlorophyll levels over 10 ug L^{-1} have been used to indicate eutrophic conditions in embayments (Cooksey et. al., 2010).

Overall, the oxygen and chlorophyll data for the Eel Pond and Childs River sub-embayments to the overall Waquoit Bay system clearly indicate that the upper reaches are presently supporting sub-tidal habitats impaired by nitrogen enrichment as seen in the large daily oxygen excursions, moderate to large oxygen depletions and high chlorophyll-*a* levels. In contrast, the lower main basin of Eel Pond is generally showing a low level of nitrogen enrichment associated with the high quality inflowing waters of Vineyard Sound and the low water quality ebb flows from the upper basins. These observations are consistent with the levels of nitrogen enrichment throughout the estuary (Section VI). The gradient in impairment follows the gradient in nitrogen enrichment, where Childs River and upper Eel Pond have very high ebb tide TN levels (>0.8 mg L^{-1} and >0.7 mg L^{-1}, respectively), declining to the lower Eel Pond basin (~0.4 mg L^{-1}). While the lower basin of the Eel Pond supports some of the lowest nitrogen levels within the overall system, the levels suggest a basin incapable of supporting eelgrass beds, but only slightly impaired to benthic animal habitat (see Sections VII-3 & VII-4, below).

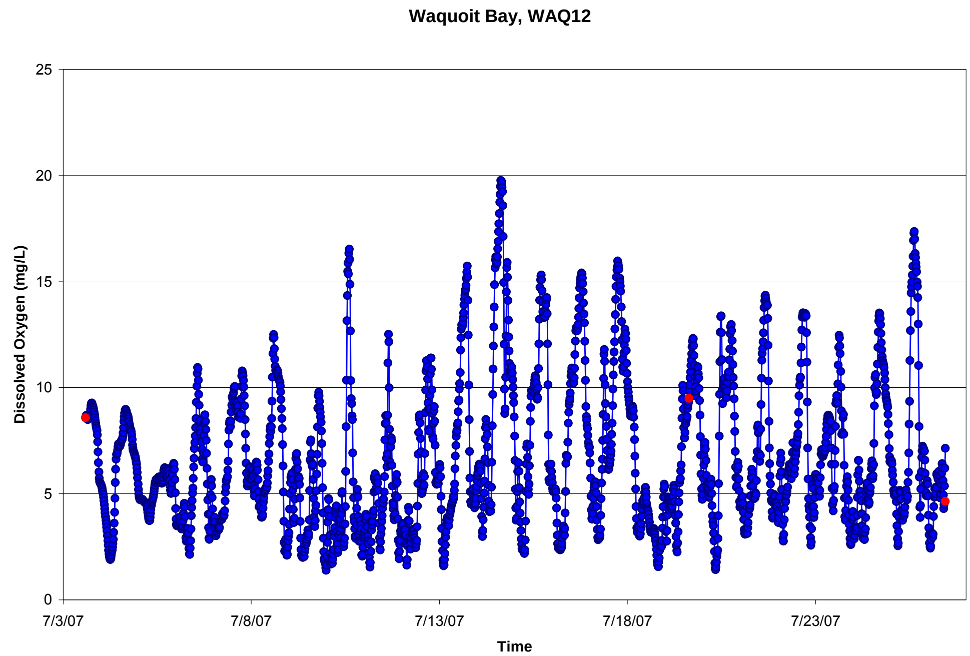


Figure VII-17. Bottom water record of dissolved oxygen within the channel of the Childs River sub-embayment (mooring WQA12), Summer 2007. Calibration samples represented as red dots.

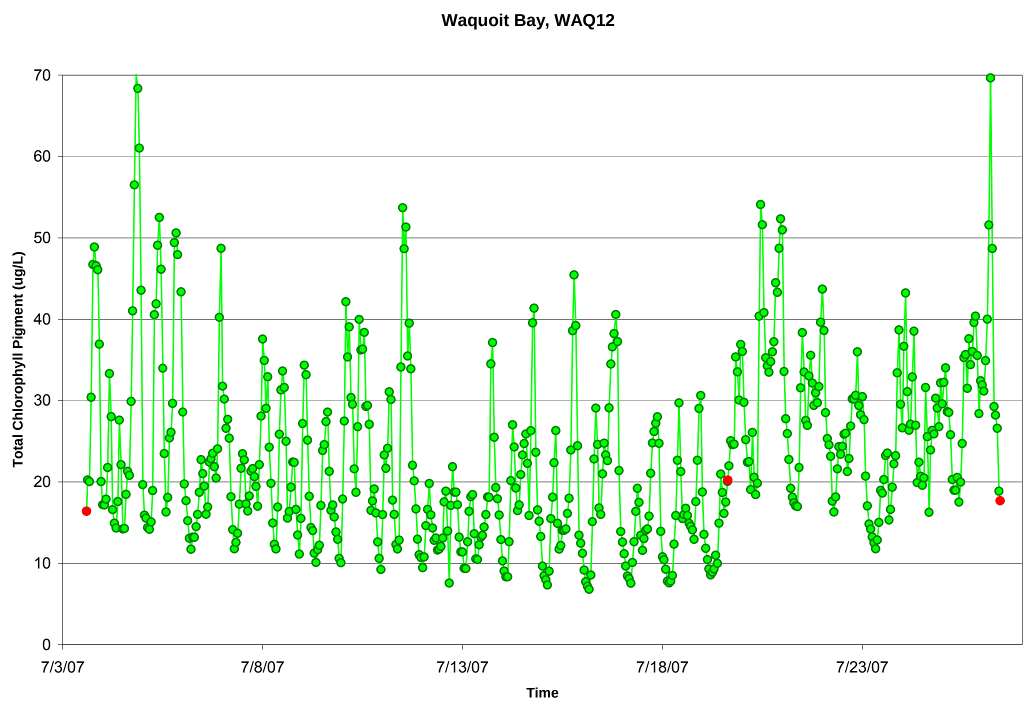


Figure VII-18. Bottom water record of Chlorophyll-*a* within the channel of the Childs River sub-embayment (mooring WQA12), Summer 2007. Calibration samples represented as red dots.

VII.2.3 BOTTOM WATER DISSOLVED OXYGEN RESULTS FOR SAGE LOT POND

In addition to the D.O. mooring program undertaken by the MEP in the eastern sub-embayments of Waquoit Bay (Quashnet River, Hamblin Pond, Jehu Pond), the western sub-embayments (Eel Pond, Childs River) and the main Waquoit Bay basin, additional time-series oxygen data were available from the WBNERR System-Wide Monitoring Program (SWMP) for Sage Lot Pond. These data were obtained for summer time conditions and were available for the years 2002-2006 (Figures VII-19, VII-20, VII-21, VII-22, VII-23 and Table VII-8). Data from the Sage Lot Pond mooring located centrally in the sub-embayment was consistent across the 5 years (2002-2006). Data collected from this location exhibited moderate diurnal dissolved oxygen excursions generally between 4 and 5 mg L^{-1}, however, DO levels were regularly below the threshold of 6 mg L^{-1} for the majority of the deployments (Table VII-8 and Figure VII-19 to VII-23). Dissolved oxygen regularly dropped below 4 mg L^{-1} and on several occasions during different deployment years dropped below 2 mg L^{-1}. DO minima and maxima appear coincident with low tides and are very likely defined by the nature of a salt marsh dominated basin. The Sage Lot Pond portion of the Waquoit Bay system is bordered by substantial areas of tidal salt marsh as well as more extensive salt marsh areas along the channel leading from the main basin of Waquoit Bay to Sage Lot Pond. Salt marsh ponds, such as Sage Lot Pond, are by nature rich in organic matter and show periodic hypoxia in summer.

The assessment that low dissolved oxygen may be driven by the fact that Sage Lot Pond is functioning primarily as a shallow tidal salt pond is supported by the pattern of oxygen decline. The organic matter enriched sediments of salt marsh tidal creeks and basins, where the organic matter enriched sediments support high levels of oxygen uptake at night, typically show oxygen depletions. While oxygen depletion to 4 mg/L would indicate impairment in an embayment like the main basin of Waquoit Bay, it is consistent with the organically enriched nature of tidal creeks. These observations are typical of other salt marsh dominated estuarine basins assessed by the MEP, for example Lewis Pond in the nearby Parkers River system (Yarmouth) as well as the lower basin of Namskaket Marsh, a healthy salt marsh in Orleans, showed a nearly identical pattern of dissolved oxygen both in the level of the oxygen excursion and the extent of oxygen depletion. Similarly, Mill Creek within Lewis Bay (Barnstable and Yarmouth, MA), showed similar periodic oxygen depletions to 4 mg L^{-1}, but is functioning as a healthy yet nutrient rich salt marsh system. Given the significant salt marsh areas in the Sage Lot Pond portion of the Waquoit Bay embayment system, the observed oxygen levels and the characteristics of the benthic community described in Section VII-4, it appears that this reach of the overall system is only moderately impaired due to the significant presence of macroalgae and the resident benthic animal community.

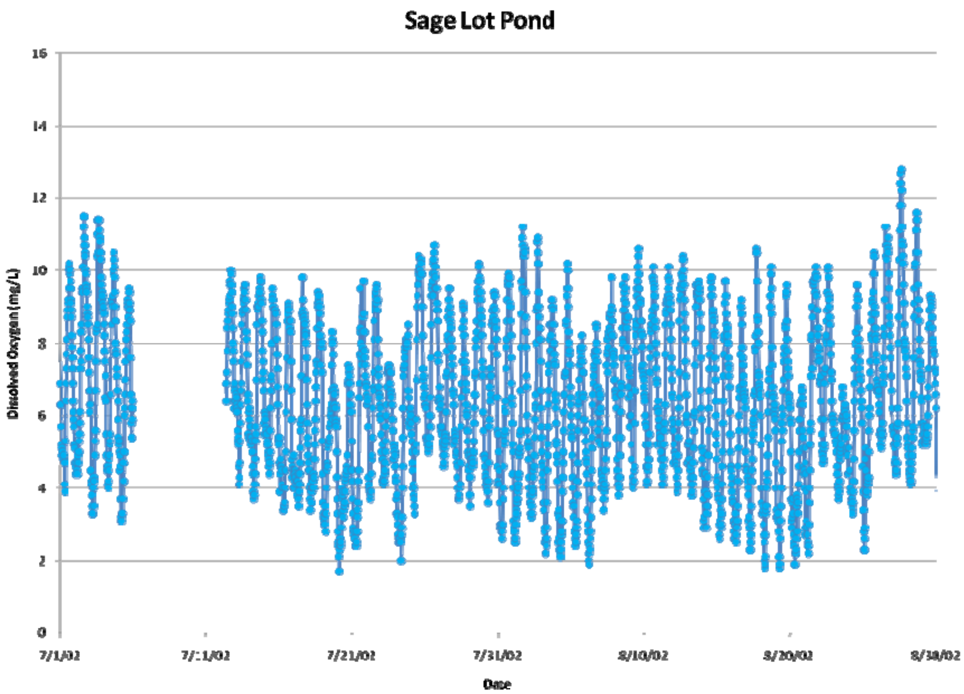


Figure VII-19. Bottom water record of dissolved oxygen within the Sage Lot Pond sub-embayment, Summer 2002 (courtesy WBNERR).

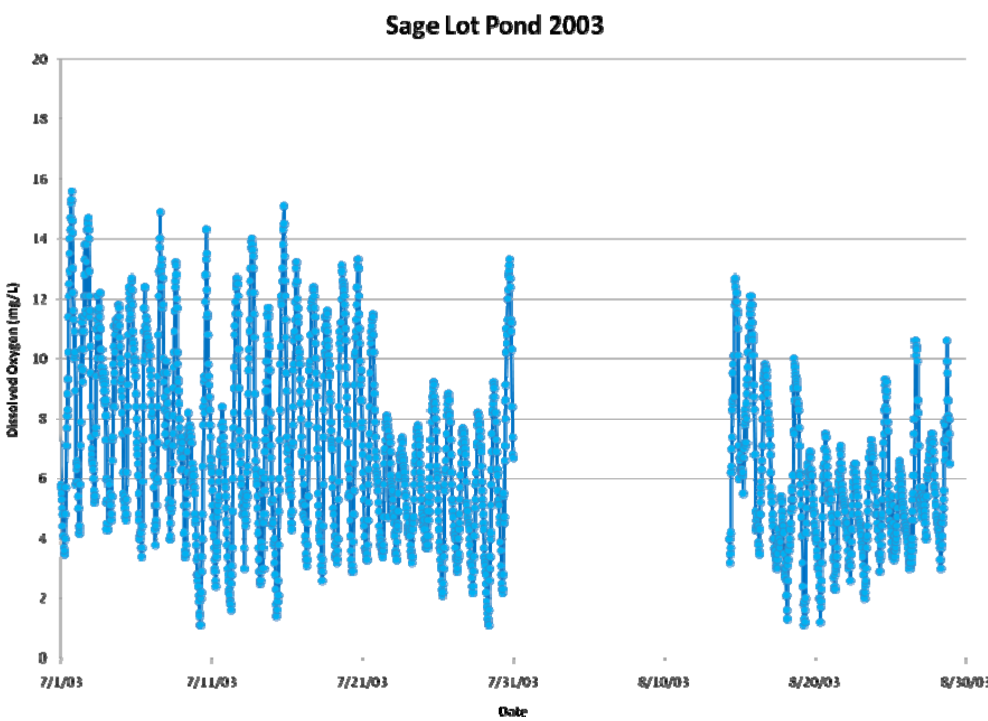


Figure VII-20. Bottom water record of dissolved oxygen within the Sage Lot Pond sub-embayment, Summer 2003 (courtesy WBNERR).

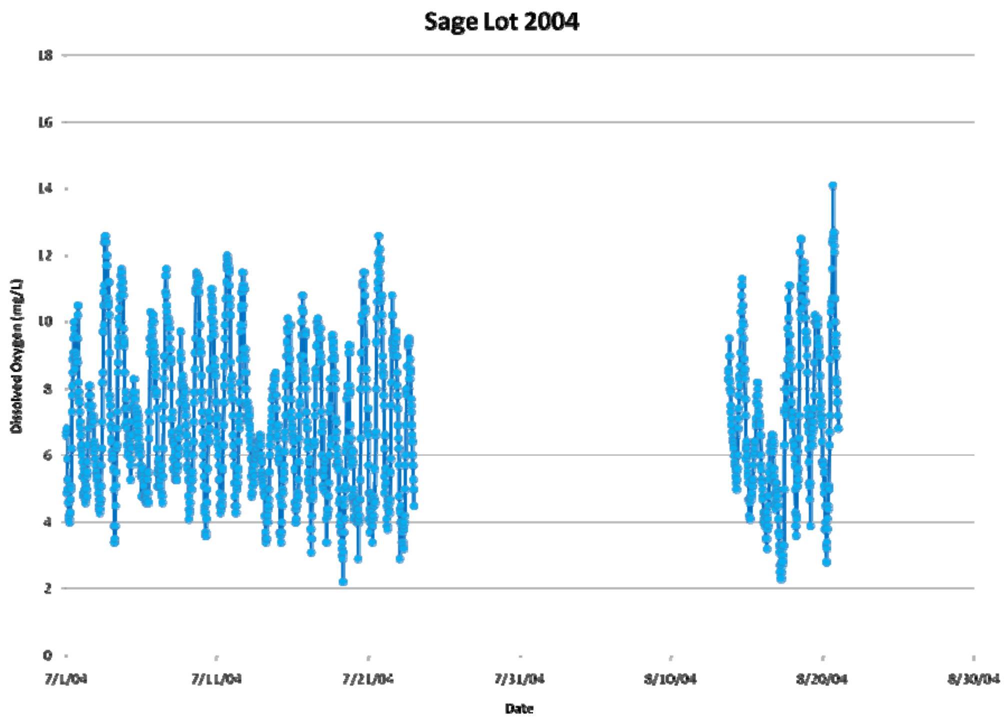


Figure VII-21. Bottom water record of dissolved oxygen within the Sage Lot Pond sub-embayment, Summer 2004 (courtesy WBNERR).

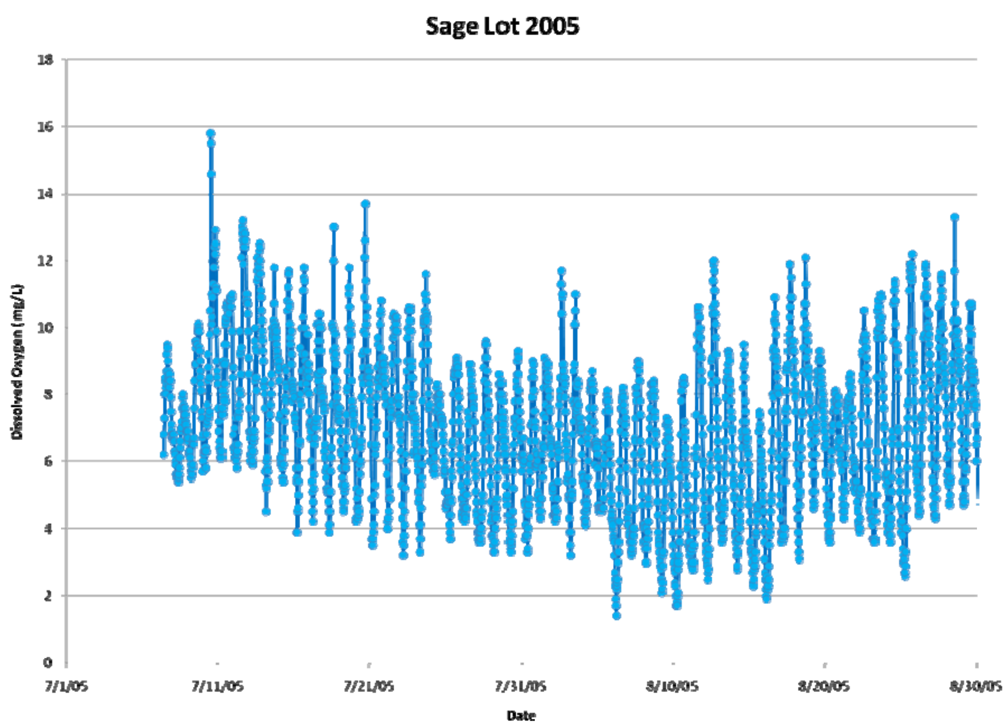


Figure VII-22. Bottom water record of dissolved oxygen within the Sage Lot Pond sub-embayment, Summer 2005 (courtesy WBNERR).

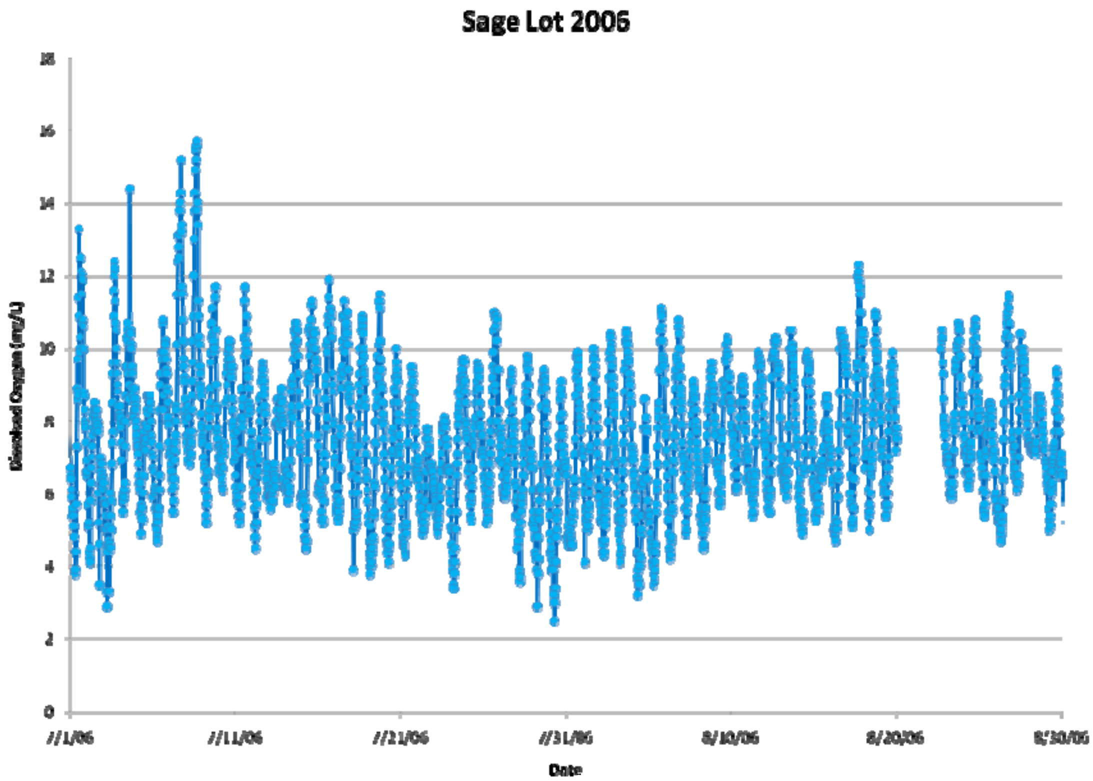


Figure VII-23. Bottom water record of dissolved oxygen within the Sage Lot Pond sub-embayment, Summer 2006 (courtesy WBNERR).

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data were conducted for the Waquoit Bay Embayment System by the DEP Eelgrass Mapping Program as part of the MEP Technical Team. Surveys were conducted in 1995 and 2001, as part of this program. Additional analysis of available high resolution aerial photos from 1951 was used to reconstruct the eelgrass distribution when the watershed was relatively undeveloped (estimated at <25% of today, Brawley et al. 2000). The 1951 data were only anecdotally validated, while the 1995 and 2001 maps were field validated. Additional high quality eelgrass coverage information for the eastern Waquoit Bay embayments from 1987-1992 was used in the temporal analysis of eelgrass distribution (Short and Burdick 1996). The primary use of the temporal data are to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1987, 1988, 1989, 1992, 1995 to 2001 (Figures VII-24 and VII-25 / VII-26); the period in which watershed nitrogen loading significantly increased to its present level. This temporal information is also used to determine the stability of the eelgrass community.

Table VII-8. Duration (percent of deployment time) that bottom water dissolved oxygen levels were below various benchmark levels within the Sage Lot Pond portion of the overall Waquoit Bay system. "Mean" represents the average duration of each event over the benchmark level and "S.D." its standard deviation. Data collected by WBNERR SWMP.

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)
Sage Lot Pond 2002	**7/1/2002**	**8/30/2002**	**55.63**	**48%**	**32%**	**16%**	**6%**
			Mean	0.36	0.26	0.16	0.12
			Min	0.02	0.02	0.02	0.02
			Max	0.79	0.73	0.54	0.27
			S.D.	0.22	0.17	0.14	0.09
Sage Lot Pond 2003	**7/1/2003**	**8/30/2003**	**44.5**	**48%**	**34%**	**19%**	**7%**
			Mean	0.37	0.28	0.17	0.10
			Min	0.02	0.02	0.02	0.02
			Max	1.48	0.67	0.44	0.29
			S.D.	0.29	0.19	0.13	0.09
Sage Lot Pond 2004	**7/1/2004**	**8/30/2004**	**30.3**	**39%**	**22%**	**7%**	**1%**
			Mean	0.28	0.14	0.07	0.05
			Min	0.02	0.02	0.02	0.02
			Max	0.65	0.46	0.29	0.08
			S.D.	0.19	0.14	0.07	0.03
Sage Lot Pond 2005	**7/1/2005**	**8/30/2005**	**54.6**	**38%**	**25%**	**11%**	**3%**
			Mean	0.28	0.24	0.15	0.11
			Min	0.02	0.02	0.02	0.02
			Max	0.75	0.63	0.48	0.29
			S.D.	0.22	0.17	0.14	0.10
Sage Lot Pond 2006	**7/1/2006**	**8/30/2006**	**58.3**	**24%**	**8%**	**2%**	**0%**
			Mean	0.19	0.10	0.06	0.04
			Min	0.02	0.02	0.02	0.02
			Max	0.60	0.40	0.17	0.06
			S.D.	0.15	0.09	0.05	0.02

The main basin of Waquoit Bay historically supported regions of significant eelgrass beds, primarily in the northern basin with large fringing beds and in the region of the tidal inlet. However, much of the central region of the lower main basin has not supported significant eelgrass resources in over 60 years. Similarly, within the western sub-embayments of Eel Pond and Childs River, significant eelgrass coverage was documented for the lower Childs River and the east branch and lower basin of Eel Pond, but not the uppermost portion of the west branch, as determined by MassDEP. It should be noted that given the configuration of the Childs River, it is likely that these beds were generally confined to the shallower margins rather than filling the basin. Over the past 60 years, virtually all of the eelgrass beds within the main basin of Waquoit Bay and Eel Pond and Childs River have been lost. Analysis of the temporal and spatial patterns of this eelgrass loss clearly indicates that it is associated with nitrogen enrichment. Nitrogen enrichment impacts in estuaries generally are highest in the upper reaches and diminish toward the tidal inlets. Initially, watershed nitrogen loading will raise the level of organic enrichment, turbidity due to phytoplankton biomass and oxygen depletion above the tolerance of eelgrass, only in the upper reaches. But as nitrogen inputs increase, the area of impact expands toward the tidal inlet. Within an individual basin, there can be another loss pattern with declines observed in the deeper portions of the basin and the last remaining beds confined to the shallow fringing areas. Both patterns are seen in the basins of Waquoit Bay.

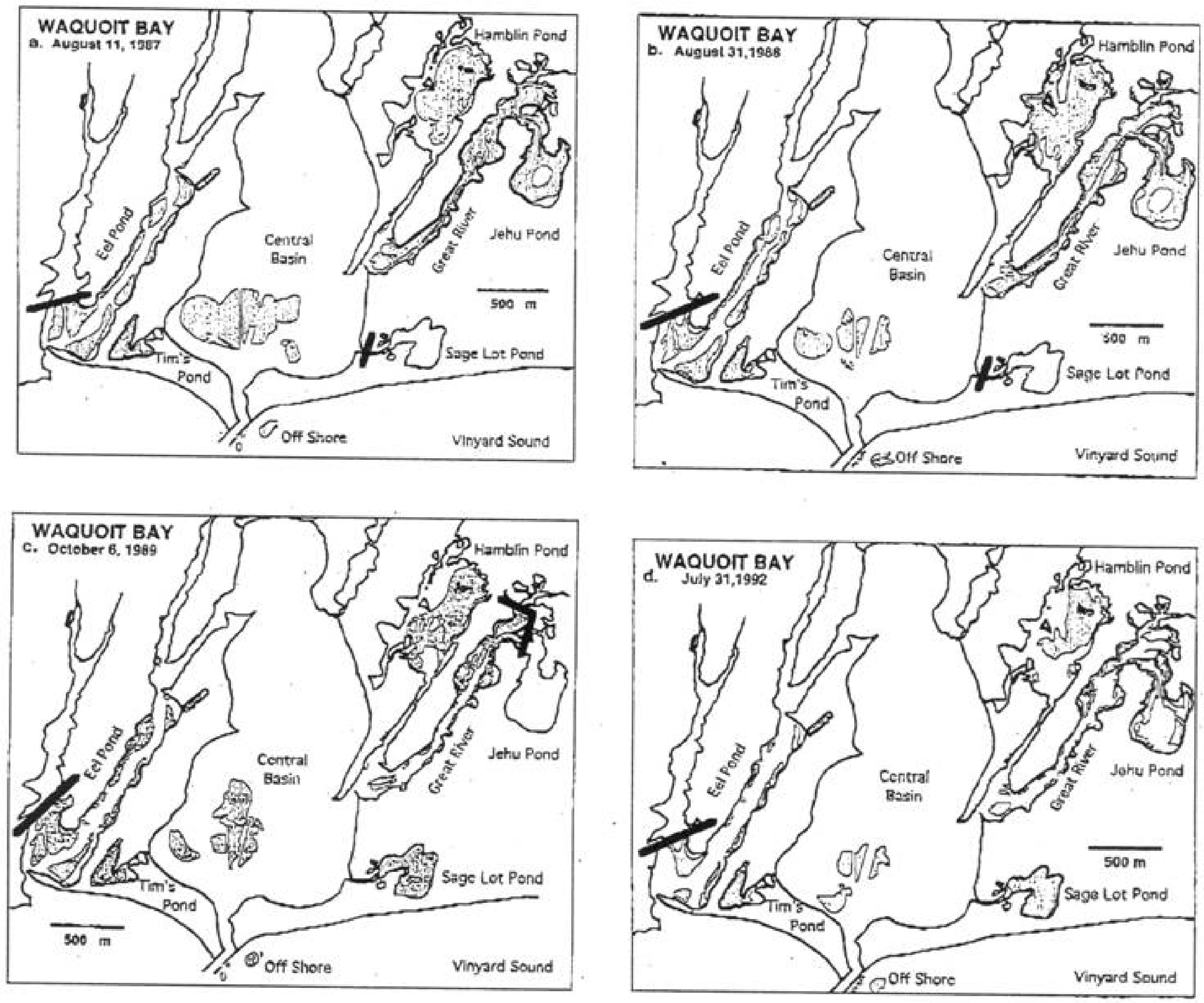


Figure VII-24. Eelgrass distribution (1987, 1988, 1989 and 1992) within the Waquoit Bay System determined with field observations (Short and Burdick 1996). Rate of loss of eelgrass is rapid in Jehu and Hamblin Ponds during this interval and continued over the next decade (Figure VII-25). Note the “hole” in the Jehu Pond coverage is in the deep basin.

Integrating all of the eelgrass coverage data, it appears that eelgrass beds declined first in the upper reaches of the main basin (and its western shallows) of Waquoit Bay and the Childs River channel, between 1951 and 1987 (Figures VII-24, VII-25). From 1987 to 1992, eelgrass beds were lost first from the deep regions of Eel Pond and then from much of the shallow margins. The result being the near complete loss of historic eelgrass coverage from the main basin of Waquoit Bay, Eel Pond and Childs River by the 1995 MassDEP field survey. No significant eelgrass coverage was observed within these basins in MassDEP field surveys in 1995 and 2001 and during the MEP sediment and benthic surveys in 2006. It should be noted that a small remnant eelgrass "bed" persisted near the tidal inlet to the main basin of Waquoit Bay until recently. Based upon the pattern of eelgrass loss and the observed levels of nitrogen enrichment, phytoplankton biomass, oxygen dynamics and organic enrichment of sediments, it can be concluded that loss of eelgrass in Waquoit Bay results from nitrogen enrichment, similar to most other documented eelgrass declines in southeastern Massachusetts and New England.

Similarly, the eastern basins of the Waquoit Bay system have also lost their eelgrass resources over the past 60 years. The Quashnet River does not have evidence of eelgrass beds within the past 60 years, likely the result of nutrient enrichment due to its large watershed and major surface water discharge. The lack of eelgrass in the Quashnet River (1951 photo-interpretation, MassDEP) is consistent with observations in the 1960's of nutrient enriched conditions and macroalgae within this sub-embayment (Curley et al. 1971). In contrast, Hamblin Pond/Little River and Jehu Pond/Great River were almost completely colonized by eelgrass in the period 1951-1987 (Figures VII-24 and VII-25). The data suggest that during the 1980's eelgrass in these tributary embayments to Waquoit Bay began to significantly decline in coverage. The decline continued and by 2001 only 5%-10% of the beds remained (Table VII-8). More recent observations indicate that the residual beds are still declining in area, with only marginal areas remaining. In addition, to the on-going DEP mapping, the more recent bed loss (since 2001) has been confirmed by the multiple MEP staff conducting sampling and the mooring studies. It appears that as these systems became nutrient enriched, that they could no longer support eelgrass beds. The proximate cause of loss is most likely related to nutrient related shifts in habitat quality, most significantly increased phytoplankton biomass as seen by high chlorophyll-*a* (turbidity/shading), resulting in decreased light penetration through the water column. However, it is likely that if nitrogen loading were to decrease, eelgrass could be restored in these basins to the 1951 pattern. This is supported by the fact that small areas still remain and that the decline from "full" coverage has been recent.

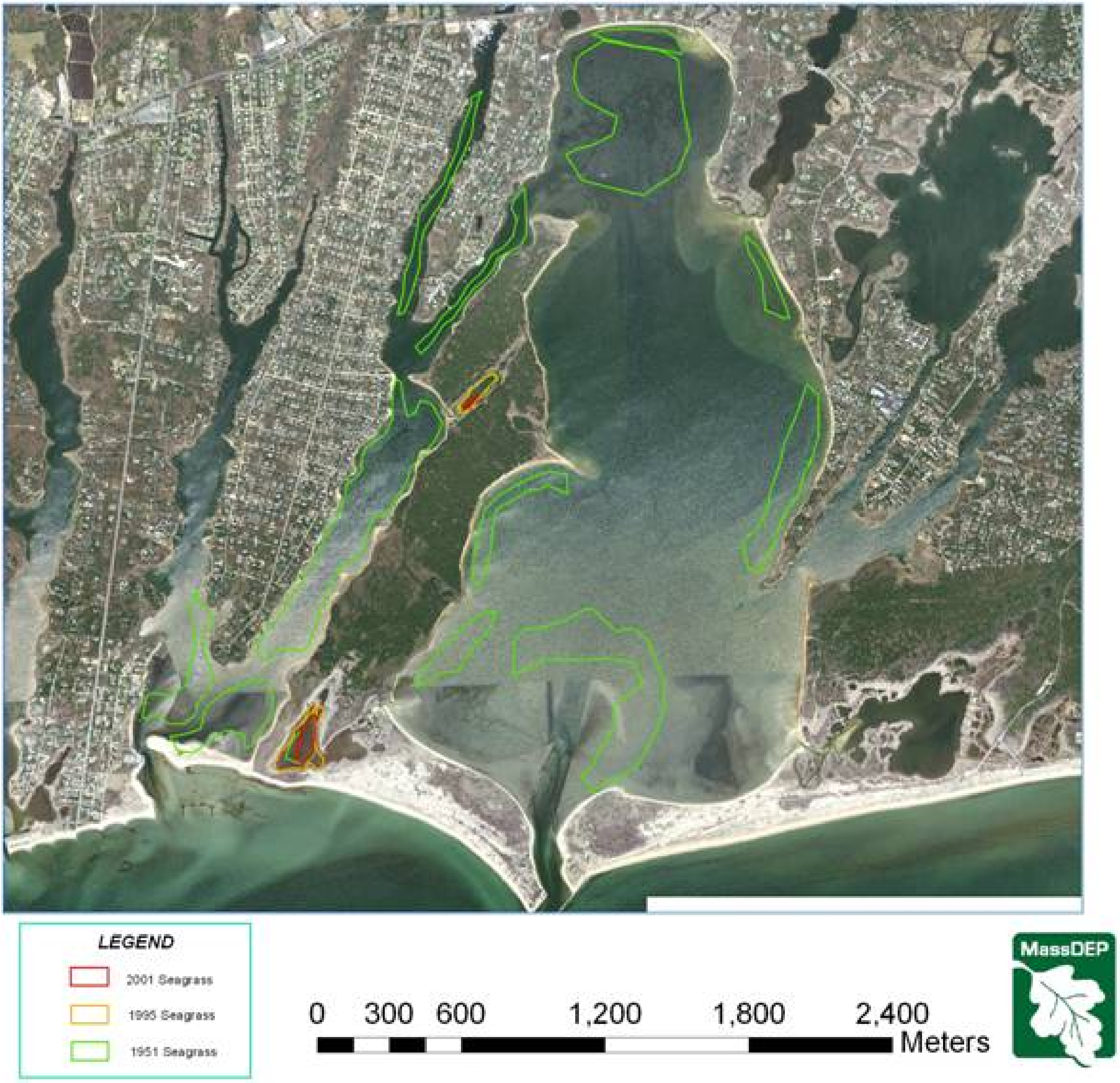


Figure VII-25. Eelgrass bed distribution within the main basin of Waquoit Bay and the Eel Pond and Childs River sub-embayments. The western sub-embayments (Sage Lot Pond, Jehu and Hamblin Ponds are not included. The eastern sub-embayments are shown in Figure VII-20. The 1951 coverage is depicted by the green outline inside of which circumscribes the eelgrass beds. The orange (1995) and red (2001) areas were mapped by MassDEP. Residual eelgrass can still be found in Sage Lot Pond and in a small area associated with the main tidal inlet. All data were provided by the MassDEP Eelgrass Mapping Program.

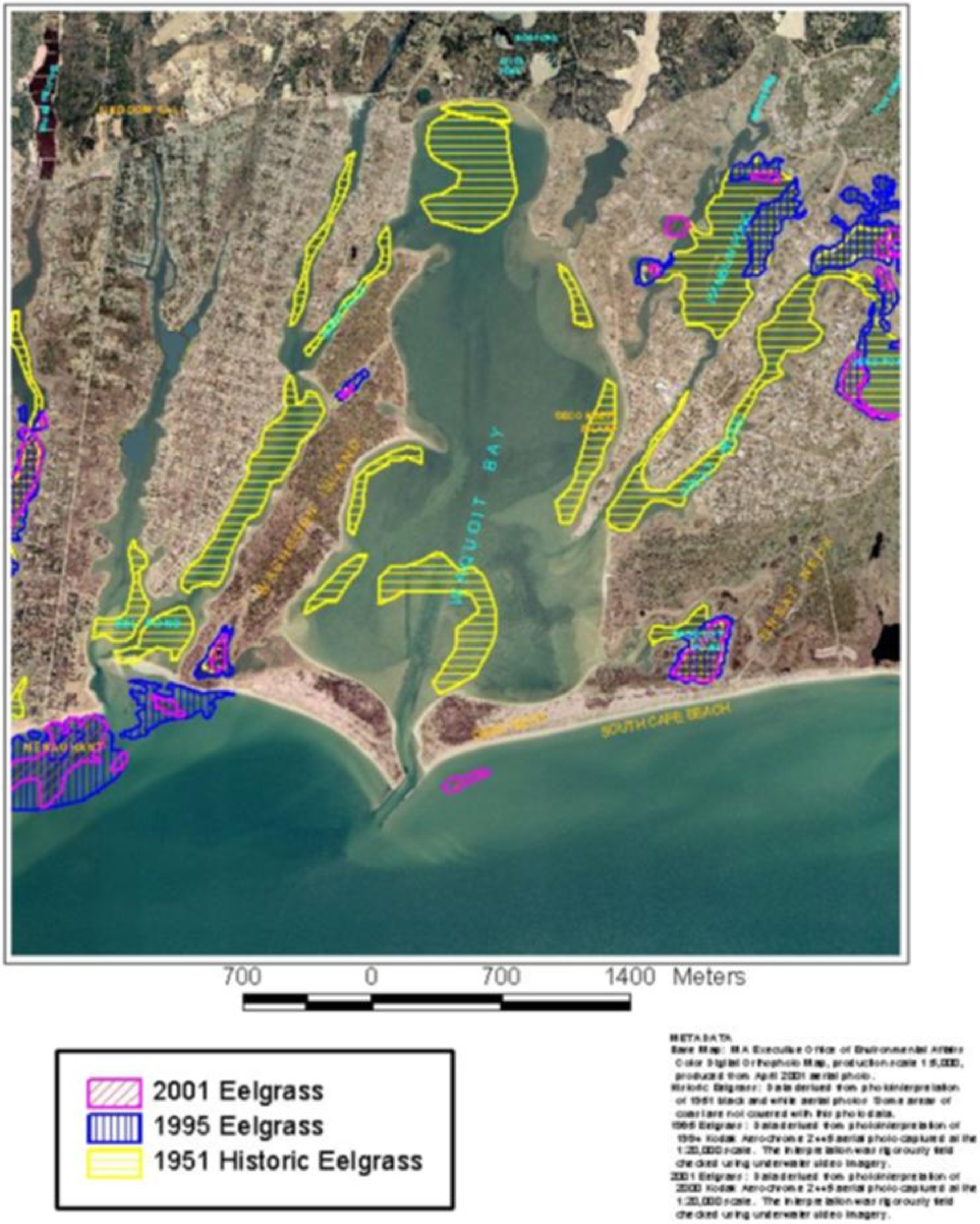


Figure VII-26. Eelgrass bed distribution within the Hamblin and Jehu Pond sub-embayment systems. The 1951 coverage is depicted by the yellow outline inside of which circumscribes the eelgrass beds. The blue (1995) and purple (2001) areas were mapped by DEP. All data were provided by the DEP Eelgrass Mapping Program.

It is significant that eelgrass was not detected in the Quashnet River Estuary in the 1951 data. The upper reaches of this sub-embayment are highly altered, but the lower basin with direct communication to the Bay also did not support beds. Part of the reason, as suggested above, may be related to higher historical nitrogen loading to this estuary, but other causes such as tidal restriction cannot be evaluated at this time.

In systems like Hamblin Pond/Little River and Jehu Pond/Great River, the general pattern is for highest nitrogen levels to be found within the innermost basins, with concentrations declining moving toward the tidal inlet. This pattern is also observed in nutrient related habitat quality parameters, like phytoplankton, turbidity, oxygen depletion, etc. The consequence is that eelgrass bed decline typically follows a pattern of loss in the innermost basins (and sometimes also from the deeper waters of other basins) first. The temporal pattern is a “retreat” of beds toward the region of the tidal inlet. However, the Hamblin Pond and Jehu Pond basins also present a modification of this general pattern, in that eelgrass beds are typically lost from the deeper waters first, due to shading effects resulting from the increased phytoplankton production. This pattern is clearly seen in Jehu Pond, where coverage was virtually complete in 1951 (Figure VII-25) but a “hole” was clearly present in 1987 (Figure VII-24), which expanded through 1992, 1995, and 2001. The two patterns of loss combine to generate the overall shifts in eelgrass distribution in these systems. Lowering of nitrogen loads to these estuaries would likely result in a reversal of this pattern with the shallower areas being the first to re-colonize.

Other factors which influence eelgrass bed loss in embayments may also be at play in the sub-embayments to the Waquoit Bay System, though the loss seems completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, as much of the loss in coverage is in areas that support few moorings. Similarly, pier construction and boating pressure may be adding additional stress in nutrient enriched areas, but do not seem to be the overarching factor. It is not possible at this time to determine the potential effect of shellfishing on eelgrass bed distribution, although it must be small as there is little shellfishing throughout much of area of recent loss. It is occasionally suggested that the loss of eelgrass in s.e. Massachusetts estuaries may be a carry-over of the historic eelgrass loss due to wasting disease. Eelgrass wasting disease, caused by a slime mold (Labyrinthula), caused significant eelgrass loss in the 1930s. However, by the 1940s Labyrinthula had ceased its catastrophic destruction and recolonization began to occur. It should be noted that not all eelgrass was lost and in some estuaries it appears that losses were minor. By the 1960s recolonization had occurred in most systems (Short et al. 1987). Therefore, the 1950 bench mark distribution developed by MassDEP for the MEP, represents a conservative coverage, since recolonization may not have been complete in specific estuaries. More importantly, the documented loss over the past 60 years occurred decades after the loss due to wasting disease, and parallels the increase in watershed nitrogen loading throughout almost all of s.e. Massachusetts estuaries.

Overall the mapping data indicate that nitrogen management of the Waquoit Bay Embayment System and specifically, Hamblin Pond and Jehu Pond, the main basin of Waquoit Bay and Eel Pond should target eelgrass restoration. Based upon the 1951-1987 coverage data, it appears that on the order of 200 acres of eelgrass might be potentially recoverable in these estuarine sub-embayments, if nitrogen management alternatives were implemented (Table VII-9).

The relative pattern of these data are consistent with the results of the benthic infauna analysis and the observed eelgrass loss is typical of nutrient enriched shallow embayments.

Table VII-9 Changes in eelgrass coverage in the Waquoit Bay System of the Towns of Mashpee and Falmouth over the past half century (DEP, C. Costello). Values base upon data in Figure VII-24, VII-25 and VII-26.

EMBAYMENT	1951 (acres)	1995 (acres)	2001 (acres)	% Difference (1951 to 2001)
Hamblin Pond / Little River	92.27	25.81	4.22	95%
Jehu Pond / Great River	115.01	48.10	12.98	89%
Waquoit Main Bay + Eel Pond	244.86	9.32	2.81	99%
Note: No historic eelgrass documented in Quashnet River				

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling for infaunal community characterization was conducted at 22 stations (Figure VII-27) throughout the main basin of Waquoit Bay and its western sub-embayments, Eel Pond and Childs River. These samples were collected in the fall of 2006. In addition, 13 locations throughout the eastern sub-embayments to Waquoit Bay (Figure VII-28) were previously collected in the fall of 2003. In all areas and particularly those that do not support eelgrass beds (e.g. most of the present Waquoit Bay System), 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, given the loss of eelgrass beds, throughout the main basin of Waquoit Bay, eastern and lower Eel Pond (fringing beds in Childs River), as well as the Quashnet River, Hamblin Pond/Little River and Jehu Pond/Great River, it is clear that the Waquoit Bay Embayment System is clearly impaired by nutrient overloading throughout its tidal reaches. However, to the extent that a system can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Section VIII).

Analysis of the evenness and diversity of the benthic animal communities was also used to support the density data and the natural history information (Table VII-10). The evenness statistic can range from 0-1 (one being most even), while the diversity index does not have a theoretical upper limit. Highest quality habitat areas, as shown by the oxygen and chlorophyll records and eelgrass coverage, generally have the highest diversity (generally >3) and evenness (~0.7). The converse is also true, with poorest habitat quality found where diversity is <1 and evenness is <0.5.

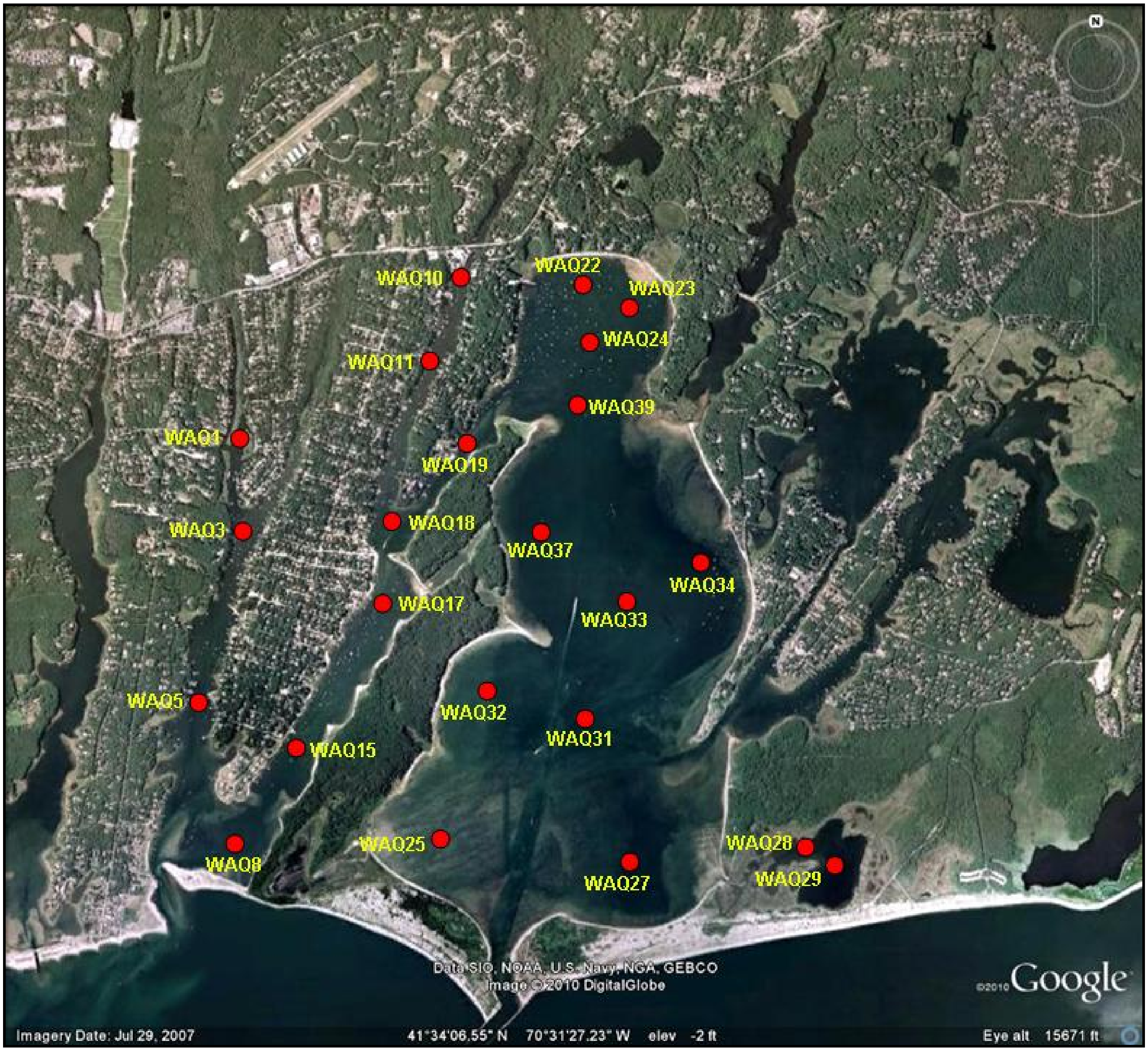


Figure VII-27. Aerial photograph of the western sub-embayments of Eel Pond and the Childs River within the Waquoit Bay System as well as the main basin of Waquoit Bay showing location of benthic sampling stations (red symbols) for infaunal community assessments.

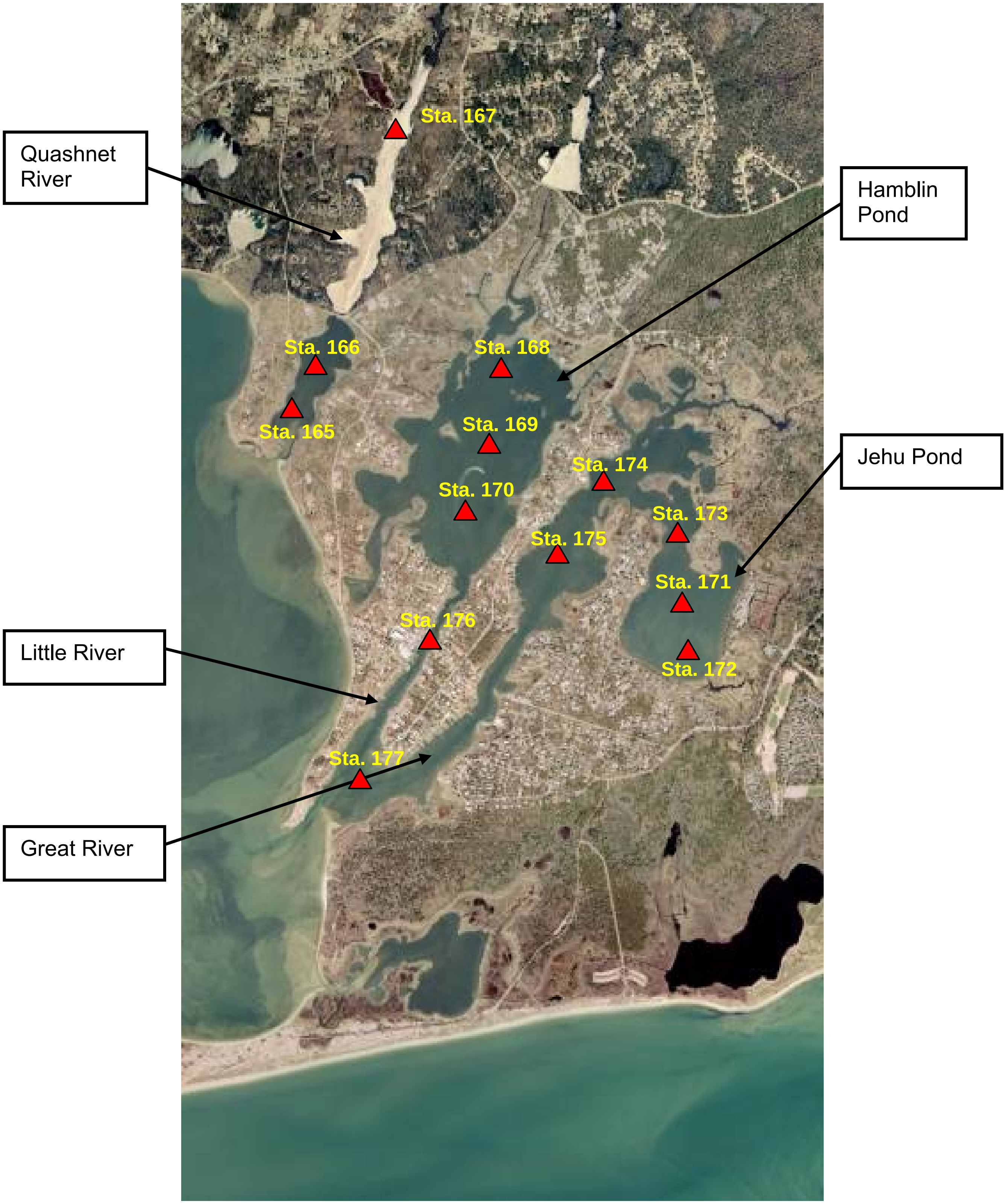


Figure VII-28. Aerial photograph of the eastern embayments within the Waquoit Bay System showing location of benthic sampling stations (red symbols) for infaunal community assessments.

Table VII-10. Benthic infaunal community data for each of the component basins of the Waquoit Bay Embayment System (Waquoit Bay, Eel Pond, Child's River, Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River and Sage Lot Pond). Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m2). Station i.d.'s refer to sites in Figures VII-27 and VII-28.

Basin	Sta-#	Total Actual Species	Total Actual Individuals	Species Calculated @75 Individ	Weiner Diversity (H')	Evenness (E)
Waquoit Bay Embayment System						
Hamblin P. - Upper	168	10	496	9	2.39	0.72
Hamblin P. - Mid	169	4	26	N/A	1.57	0.79
Hamblin P. - Lower	170	18	793	9	2.42	0.58
Little River - Mid	176	19	3170	10	2.74	0.65
Jehu Pond - Upper	171	4	34	N/A	1.74	0.87
Jehu Pond - Mid	172	6	144	N/A	1.79	0.69
Jehu Pond - Lower	173	4	401	4	1.38	0.69
Great River	174,175	10	1608	7	1.97	0.61
Grt/Little Confluence	177	4	14	N/A	1.84	0.92
Quashnet R. - Upper	165	1	18	N/A	0.00	N/A
Quashnet R. - Lower	166, 167	1	2	N/A	0.00	N/A
Eel Pond - West	Waq-1,3,5	8	273	4	1.48	0.50
Eel Pond - East	Waq-8	18	1232	12	2.37	0.57
Eel Pond - Basin	Waq-15,17,18	23	2146	13	2.58	0.57
Child's River	Waq-10,11	11	347	7	1.87	0.56
Seapit River	Waq-19	33	1868	16	3.34	0.66
Waquoit Bay - North	Waq-22,24,39	15	1323	10	2.33	0.60
Waquoit Bay - South	Waq-25,27,31-34,37	13	478	9	2.02	0.56
Sage Lot Pond	Waq-28,29	10	1118	8	2.02	0.62

Based upon the infaunal community survey it appears that most of the Waquoit Bay Embayment System is presently supporting impaired benthic animal habitat, primarily resulting from nitrogen and organic enrichment, periodic oxygen stress and in some areas, accumulations of drift macroalgae that "smother" benthic animals. At present, high quality benthic habitat is only found within the lower basin of Eel Pond and the Seapit River. These areas do not have significant accumulations of macroalgae or oxygen depletion and have relatively oxidized sediments comprised of medium to fine sands with low organic enrichment or consolidated muds, likely the result of high tidal flows. The lower basin of Eel Pond has large tidal flows and access to the high quality waters of Vineyard Sound on the flooding tide. The benthic animal community is moderately diverse (H'=2.58) with moderate Evenness (E=0.57), and supports a moderate to high number of species (23) and large number of individuals (>1000), with some patches of amphipods mats, indicative of a low to moderate level of impairment. Benthic animal habitat impairment is completely in-line with the low to moderate levels of oxygen stress, organic enrichment and inflows of poor quality waters as the upper basins of Eel Pond and the Childs River enter on ebbing tides. The Seapit River presently shows the highest quality benthic animal habitat within the estuary, supporting a productive community with high numbers of individuals (>1000) and species (33), with high diversity (H'=3.34) and Evenness (E=0.66), comprised of crustaceans, mollusks and polychaetes with some deep burrowers. The eastern branch of Eel Pond, between Seapit River and Eel Pond showed moderate level of habitat quality (lower than Seapit River of lower basin of Eel Pond) also with high numbers of individuals (>1000), but only moderate numbers of species (18) moderate diversity (H'=2.37). The slightly greater impairment of this habitat likely results from high nutrient and organic matter, low oxygen inflows discharges from the Childs River.

In contrast, the upper reach of the western branch of Eel Pond and the Childs River are showing significant impairment of their benthic animal habitat. These basins support low to moderate numbers of species (8-11) and moderate numbers of individuals (~300), with low diversity (H'= 1.48, 1.87) and Evenness (E= 0.50, 0.56) and a community dominated by organic tolerate species, with some stress indicators (Childs River, *Capitella* = 29% of population). The observed benthic communities are consistent with the accumulations of drift macroalage, high chlorophyll levels (~20 ug L^{-1}) and significant oxygen depletions (<4 mg L^{-1}) with periodic oxygen declines to < 3 mg L^{-1}. Sediments are organic enriched soft muds, frequently covered by accumulations of drift macroalgae.

The main basin of Waquoit Bay showed a gradient in benthic habitat quality, with the upper northern basin supporting a productive animal community, dominated by transitional species structured primarily as an amphipod mat (*Ampelisca*). The present benthic community consists of a moderate number of species (15) with high numbers of individuals, low numbers stress indicator species, moderate diversity (H'=2.3) and Evenness (E=0.60. Amphipod mats are indicative of a transitional community and are frequently found in moderately impaired organic enriched environments, sometimes with some disturbance (e.g. harbors). In contrast, the benthic habitat within the southern portion of the main basin is clearly significantly impaired. Much of the impairment derives from the ubiquitous dense accumulations of drift macroalgae. As a result the community has low to moderate numbers of species (13) with moderate-high numbers of individuals, dominated by crustaceans with some patches of amphipod mats (in open areas); low diversity (H'=2.0) and Evenness (E=0.56). The crustaceans appear to be primarily species that graze on algae or algal mats, with few deep burrowers. Within this basin it appears that organic enrichment is primarily through macroalgae and to a lesser extent phytoplankton as water column chlorophyll-*a* was only moderate (averaging ~6.5 ug L^{-1}). While periodic stressful oxygen levels occur, the oxygen concentrations experienced by benthic animals beneath the macroalgal accumulations are certain to be lower and more stressful than measured. Restoration of benthic habitat in this large basin will require nitrogen management to lower macroalgal production, hence accumulations.

Clearly, the Quashnet River Estuary is supporting severely degraded benthic habitat consistent with the above oxygen and organic enrichment metrics, with only a single species being found, hence a diversity equal to 0. The severely degraded nature of this habitat is underscored by the virtual absence of an infaunal community with only 18, 4, and 0 individuals being found at the three sites, compared to 100's to 1000's being found at healthy sites. The Jehu Pond and Hamblin Pond systems showed infaunal community habitats ranging from healthy to significantly impaired. There appears to be a gradient in habitat quality within the Jehu Pond/Great River Estuary. The basin of Jehu Pond supported a low number of species (4-6) and total individuals <150 at two of three stations and low diversity at all stations (<1.8). However, the Great River showed markedly better habitat, with 9-10 species and >1000 individuals per sample at each station, and slightly higher diversity. Hamblin Pond/Little River showed a similar pattern, although with much better habitat quality. Only the mid basin of Hamblin Pond was significantly impaired with all of the other stations showing 10-19 species and 500-3200 individuals per sample. Diversity was also high, generally ≥2.4. Most likely deposition within the mid basin of Hamblin Pond and subsequent organic matter loading effects are responsible for the observations at this station. However, the other areas of this system appear to support healthy benthic habitat (Lower Hamblin Pond and Little River) or habitat that is only moderately impaired (Upper Hamblin Pond).

Sage Lot Pond is a small salt marsh dominated pond tributary to the lower portion of the southern main basin of Waquoit Bay. As a wetland dominated salt pond, Sage Lot Pond is naturally nutrient and organic matter enriched. The high productivity (individuals >1000) and low species numbers (10) are consistent with this type of ecosystem (but not open water embayments). However, it is clear that even for a salt marsh pond, this system is presently supporting impaired benthic habitat due to the dominance of macroalgal associated crustaceans and stress indicator species (*Capitella*, 39% of population).

The benthic animal communities within the component basins of the Waquoit Bay Embayment System were compared to high quality environments, providing additional confirmation of the level of habitat impairment. The Outer Basin of Quissett Harbor supports benthic animal communities with ≥28 species, >400 individuals with high diversity (H' ≥3.7) and Evenness (E ≥0.77). Similarly, outer stations within Lewis Bay (Barnstable) currently support benthic habitat with high numbers of individuals (502 per sample), species (32), and high diversity (3.69) and Evenness (0.74). Equally important, these communities are not consistent with nutrient enrichment being composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms (tubificids, capitellids). The moderately impaired areas of the lower basin and eastern branch of Eel Pond are similarly configured to the lower reach of Parker's River (near inlet, but with poor water quality waters entering from upper reach on ebbing tides) which currently supports higher species numbers (27 species), but with only moderate diversity (h'=2.94) and Evenness (E=0.61), indicative of a low to moderate level of impairment.

Overall, the pattern of infaunal habitat quality throughout the Waquoit Bay Embayment System is consistent with measured dissolved oxygen concentrations, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily includes the structure of the specific estuarine basin, specifically as to whether a basin area is wetland influenced or an open water tidal embayment. Based upon this analysis it is clear that most of the benthic animal habitat within the Waquoit Bay Embayment System is moderately to significantly impaired (Quashnet River, severely degraded) by nitrogen and organic matter enrichment, while the moderate to high quality benthic animal habitat is primarily found in the region of the Seapit River down to the Eel Pond inlet. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the significantly impaired basins presently range from 0.65 to 1.20 mg N L^{-1}, levels typical of other estuarine basins with significant impairment of benthic animal habitat throughout southeastern Massachusetts estuaries.

Other Resource Characteristics:

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth and available. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the growth and propagation of the variety of shellfish species common to the region (Figure VII-29). As is the case with many estuaries on Cape Cod, the main open water basins of the Waquoit Bay Embayment System are open to shellfishing throughout the year, with the upper reaches of some of the enclosed basins being closed for a portion of the year. The upper tidal reach of the west branch of Eel Pond, the upper reach of the Childs River and the upper reach of Hamblin Pond are conditionally approved for the taking of shellfish during specific portions of the year, while shellfishing within the Quashnet River is prohibited year around. This likely results from bacterial contamination from human activity (failed septic systems, direct stormwater inflows) as well as natural fauna and wetland runoff. These classifications indicate that portions of the overall system are moderately to significantly impaired relative to the taking of shellfish. However, it should be noted that most of the Waquoit Bay Estuary, specifically the main basin of Waquoit Bay, Jehu Pond, most of Eel and Hamblin Ponds, and Sage Lot Pond are approved for shellfishing year round.

Despite the ability to harvest shellfish (shellfish area classifications), the Waquoit Bay System has also been assessed by MDMF as to the suitability for supporting specific shellfish populations (Figure VII-30 and VII-31). The major shellfish species with potential habitat within the main basin of Waquoit Bay are bay scallops and quahogs (*Mercenaria*). The shallow waters fringing the main basin of the bay are also classified as suitable habitat for soft shell clams (*Mya*). That classification extends to the shallow margins of Eel Pond and the Childs River as well as parts of Hamblin Pond and Jehu Pond. Eel Pond, Childs River, Hamblin Pond and Jehu Pond are also classified as areas that would theoretically be suitable for quahogs (*Mercenaria*). It should be noted that bay scallop habitat has been significantly reduced by the loss of eelgrass associated with nitrogen enrichment. Historically, Waquoit Bay supported an annual harvest of bay scallops that has become minimal with the impairment of benthic animal habitat throughout most of the estuary. To the extent that water quality and bottom water oxygen conditions can be improved through nutrient load reductions from the watershed to Waquoit Bay, benthic habitat is likely to be restored and become supportive of more diversified infaunal communities.

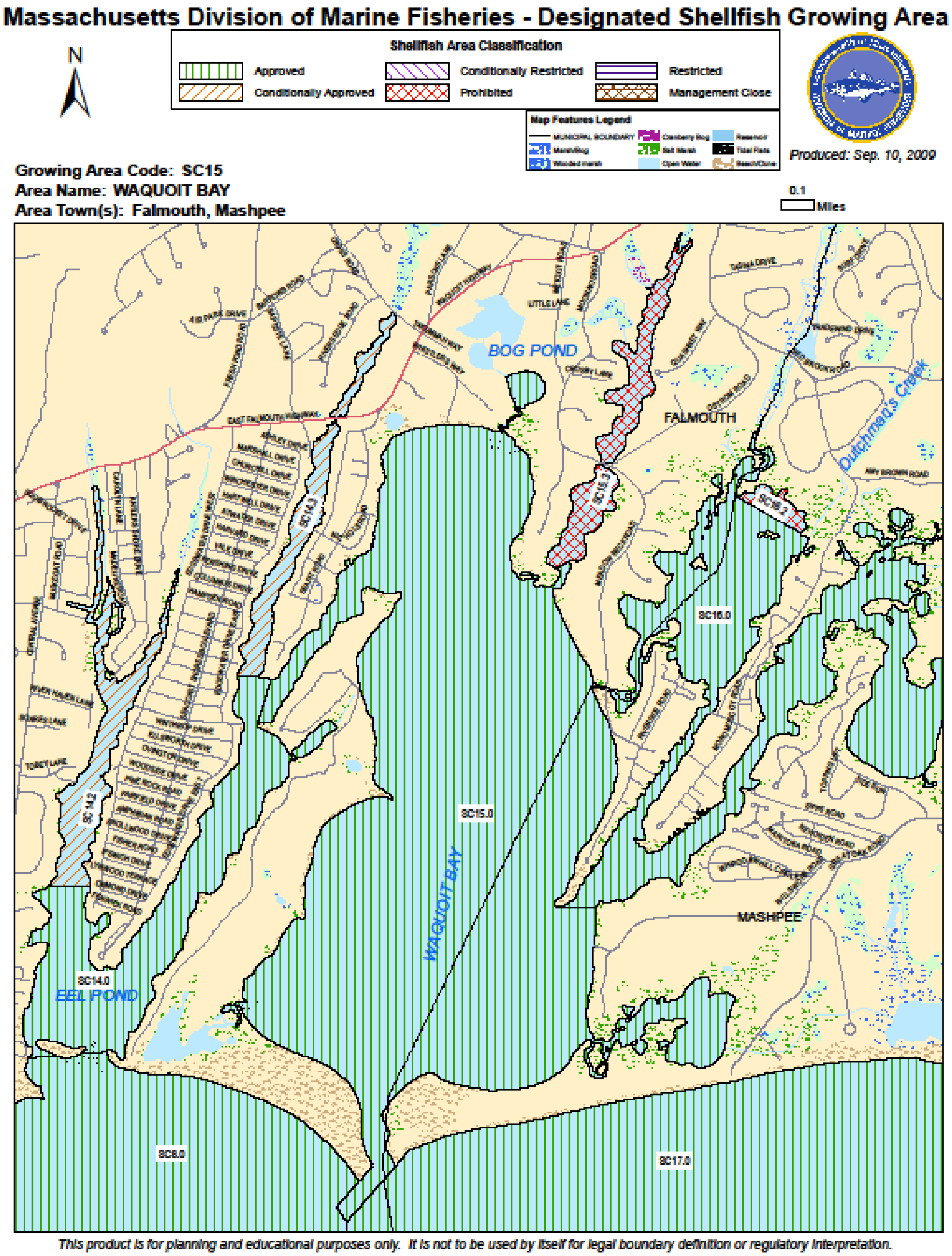


Figure VII-29. Waquoit Bay Embayment System status relative to the ability to harvest shellfish based upon bacterial levels, as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination potentially from human activities or wildlife or in water human "activities", such as the location of marinas and boat mooring fields.

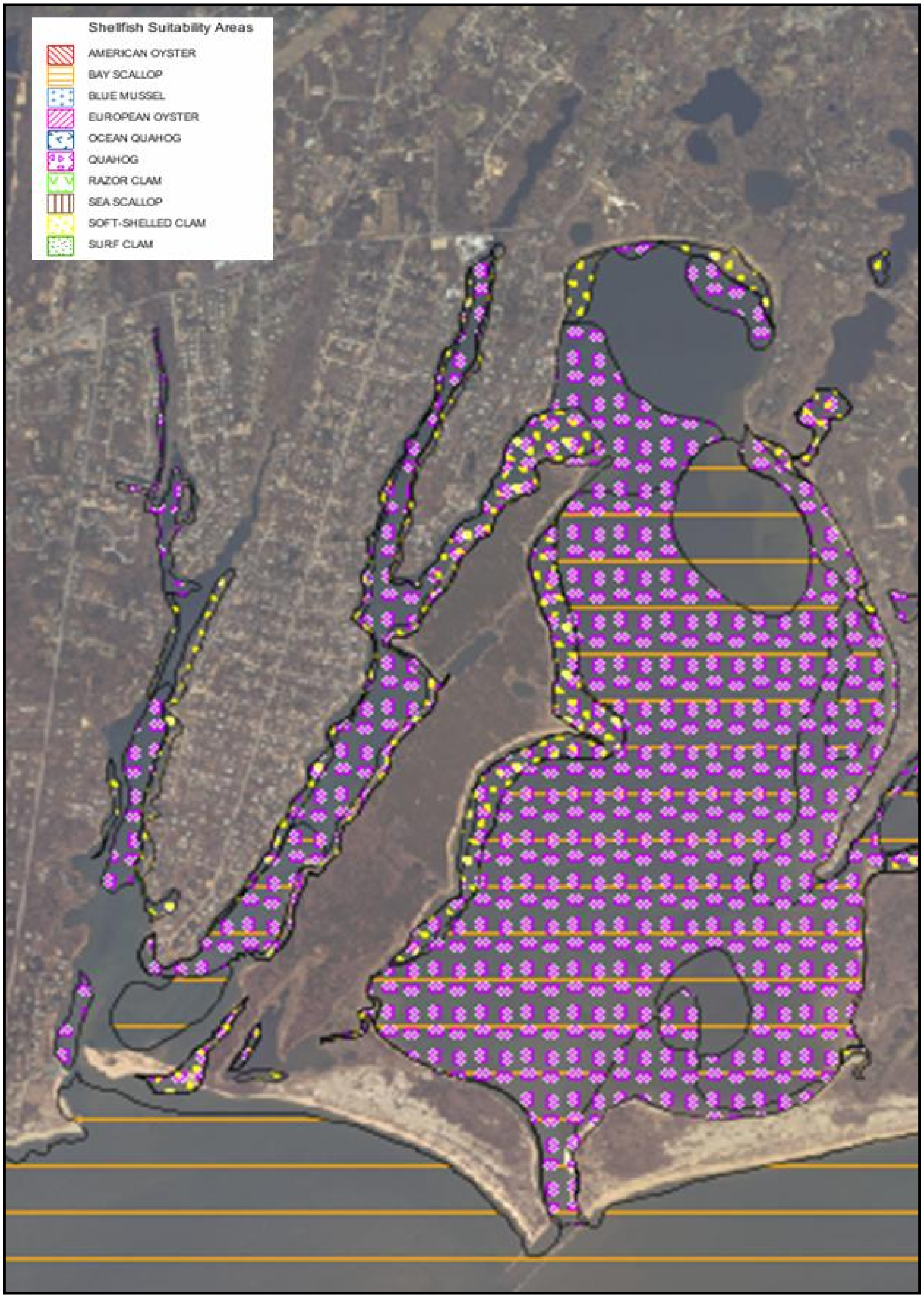


Figure VII-30. Location of shellfish suitability areas within the Eel Pond, Childs River and main basin of the Waquoit Bay Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

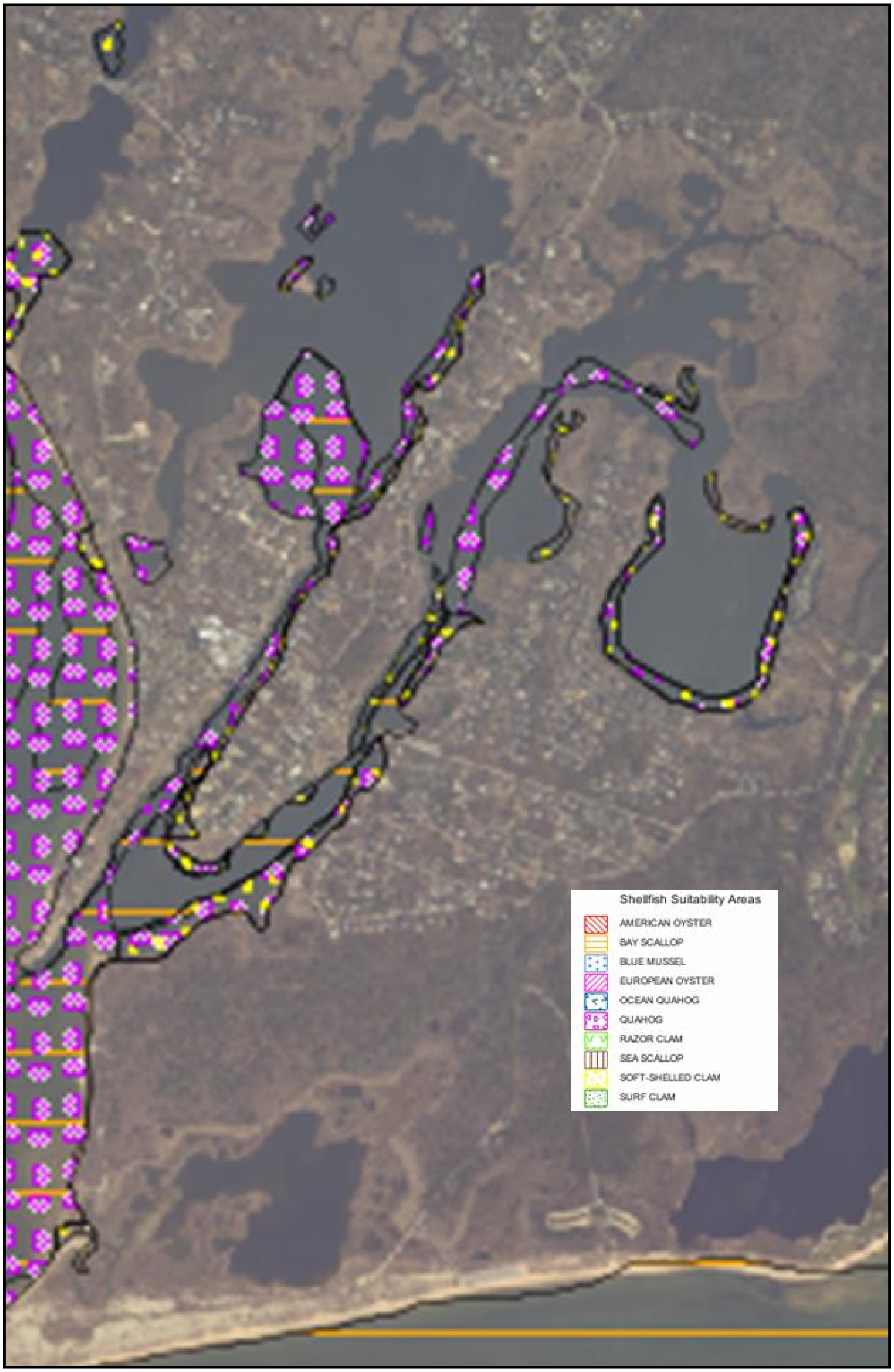


Figure VII-31. Location of shellfish suitability areas within the Hamblin Pond and Jehu Pond sub-embayments to the Waquoit Bay Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

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

VIII.1 ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires the integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll-a). Additional information on temporal changes within each sub-embayment and its watershed further strengthen the analysis. These data were collected by the MEP Team to support threshold development for the Waquoit Bay Embayment System (Waquoit Bay, Eel Pond, Childs River, Quashnet River, Sage Lot Pond, Hamblin Pond/Little River and Jehu Pond/Great River) and were discussed in Chapter VII. Nitrogen threshold development builds on these data and links habitat quality to summer water column nitrogen levels from the nitrogen modeling and baseline Mashpee Water Quality Monitoring Program (Chapter VI). At present these three estuaries are generally showing impaired habitat quality resulting from nitrogen enrichment (Chapter VII, Table VIII-1).

Eelgrass: Eelgrass surveys and analysis of historical data for the Waquoit Bay Embayment System indicated that eelgrass beds, when the watershed was relatively undeveloped (1951), were generally found within each sub-embayment, with the exception of Quashnet River and the uppermost portion of the western branch of Eel Pond. In contrast, presently virtually all eelgrass has been lost from the Waquoit Bay Embayment System, with the exception of Sage Lot Pond and a possible remnant patch associated with the main tidal inlet to Waquoit Bay. All of the basins with well documented historic eelgrass coverage within this system, which no longer support eelgrass coverage, are classified as significantly impaired relative to eelgrass habitat by the protocols of the MEP.

Multiple lines of evidence clearly indicated that the main basin of Waquoit Bay historically supported significant eelgrass coverage, primarily in the northern basin (large fringing beds) and in the region of the tidal inlet, although there is no evidence of coverage in central region of the lower main basin over the past 60 years. Similarly, within the western sub-embayments significant eelgrass coverage has been documented for the lower Childs River and the east branch and lower basin of Eel Pond, with no historic documented beds in the west branch. It should be noted that given the configuration of the Childs River, it is likely that the historic beds were primarily confined to the shallower margins rather than filling the basin. Over the past 60 years, virtually all of the eelgrass beds within the main basin of Waquoit Bay, Eel Pond and Childs River have been lost. Analysis of the temporal and spatial patterns of this eelgrass loss clearly indicates that it is associated with nitrogen enrichment. The present levels of nitrogen, chlorophyll, periodic oxygen depletion and accumulations of macroalgae support this mechanism of eelgrass decline in these basins.

Integrating all of the eelgrass coverage data, it appears that eelgrass beds declined first in the upper reaches of the main basin (and its western shallows) of Waquoit Bay and the Childs River channel, between 1951 and 1987. From 1987 to 1992, eelgrass beds were lost first from the deep regions of Eel Pond and from much of the shallow margins. The result being the near complete loss of historic eelgrass coverage from the main basin of Waquoit Bay, Eel Pond and Childs River by the 1995 MassDEP field survey. It should be noted that a small remnant eelgrass "bed" persisted near the tidal inlet until recently. Based upon the pattern of eelgrass loss and the observed levels of nitrogen enrichment, phytoplankton biomass, oxygen dynamics and organic enrichment of sediments, it can be concluded that loss of eelgrass in Waquoit Bay results from nitrogen enrichment, as for most other documented eelgrass declines in southeastern Massachusetts and New England.

Similarly, the eastern basins of the Waquoit Bay have also lost their eelgrass resources over the past 60 years. Both the Hamblin Pond/Little River and Jehu Pond/Great River were almost completely colonized by eelgrass in the period 1951-1987 (Figures VII-7, VII-8). The data suggest that during the 1980's eelgrass in these tributary embayments to Waquoit Bay began to significantly decline in coverage. The decline has continued, with less than 5%-10% of the beds remaining today (Table VII-4). It appears that as these systems became nutrient enriched, these sites could no longer support eelgrass beds. The proximate cause of loss is most likely due to nutrient related shifts in habitat quality, most significantly the high chlorophyll-a (turbidity/shading) and low dissolved oxygen levels. However, it is likely that if nitrogen loading were to decrease, eelgrass beds could be restored in these basins. Based upon the 1951-1987 coverage data, it appears that on the order of 200 acres of eelgrass might be recoverable in these estuaries, if nitrogen management alternatives were implemented (Table VII-4). This is supported by the fact that small areas of eelgrass still remain and that the decline from "full" coverage has been recent (~20 yrs). Given the significant loss of coverage, but the persistence of small patches of eelgrass in both of these systems, it appears that these estuaries are moderately impaired by nitrogen enrichment based upon this indicator alone. It is clear that nitrogen threshold development for the Hamblin Pond/Little River and Jehu Pond/Great River Estuaries should target restoration and maintenance of eelgrass habitat.

At present, eelgrass is not present within the Quashnet River estuary, nor was there evidence of eelgrass beds in 1951. This is consistent with observations in the 1960's of nutrient enriched conditions and macroalgae within this sub-embayment (Curley et al. 1971). In fact, large macroalgal accumulations occur within this estuary today and are indicative of severe degradation by nitrogen enrichment. The upper reaches of the Quashnet River Estuary have been highly man-altered which may relate to historical absence of eelgrass, but the lower basin proximal to the Bay also did not historically support beds. Part of the reason, as suggested above, may be related to higher historical nitrogen loading to this estuary, but other causes such as tidal restriction cannot be evaluated at this time. The Quashnet River inlet to Waquoit Bay has significant sediment movement which may periodically restrict tidal flows. To the extent that this has occurred in the past, it may also partially relate to the lack of historical eelgrass beds in this lower basin. It may also be that this system is not supportive of this type of habitat due to its physical properties, and stronger estuarine circulation than the other sub-embayments. Based upon history of nitrogen enrichment, the absence of eelgrass in the 1951, the Quashnet River Estuary appears to be significantly impaired/degraded relative to eelgrass. However, given the uncertainties and the lack of historical support for eelgrass in this system, it is not prudent to target restoration thresholds on this parameter. Habitat quality for infaunal communities appears to be the threshold based upon the available data and uncertainties.

Sage Lot Pond is a small salt marsh pond tributary to the lower portion of the southern basin of Waquoit Bay. As a salt marsh pond, it is naturally nutrient and organic matter enriched. However, the eelgrass within this basin is generally covered with epiphytes and the basin is accumulating drift macroalgae. Similarly, the benthic community is indicative of organic over-enrichment, as seen by the dominance of stress indicator species. All of the water quality, benthic community and eelgrass metrics indicate that this system is beyond its nitrogen tolerance level and that the eelgrass habitat is being impaired. However, as the basin continues to support eelgrass coverage it is presently moderately impaired relative to eelgrass habitat.

The near complete loss of the extensive eelgrass beds within the Waquoit Bay Embayment System has paralleled the increase in watershed development and the associated nitrogen enrichment to the System's estuarine waters. It appears that as the component sub-embayments became nutrient enriched, they could no longer support eelgrass beds. The proximate cause of loss is most likely related to nutrient related shifts in habitat quality, most significantly increased phytoplankton biomass as seen by high chlorophyll-a (turbidity/shading), resulting in decreased light penetration through the water column. However, it is likely that if nitrogen loading were to decrease, eelgrass could be restored in these basins to the 1951 pattern. This is supported by the fact that small areas still remain and that the decline from "full" coverage has been relatively recent.

Water Quality: The water quality indicators that are central to evaluating the nutrient related habitat health for eelgrass and benthic infaunal communities are the degree of oxygen depletion in bottom waters and the level of phytoplankton biomass (blooms) as determined from total chlorophyll-a measurements.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a levels within the main Basin (north and south) of Waquoit Bay indicate high levels of nutrient enrichment and impaired habitat quality. The oxygen data are consistent with high organic matter loads and the moderate levels of phytoplankton biomass (chlorophyll-a levels) indicative of nitrogen enrichment of this estuarine basin. The large daily excursions in oxygen concentration in the main basin of Waquoit Bay, from the head (~3 mg L^{-1}) to middle (5-7 mg L^{-1}) to the lower portion close to the inlet (5 mg L^{-1}), are clear indications of significant organic matter enrichment and estuarine waters with an unstable oxygen balance. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration throughout Waquoit Bay and its sub-embayments is further evidence of nitrogen enrichment at a level consistent with habitat degradation.

Oxygen conditions within the northern portion of the main basin of Waquoit Bay showed low to moderate levels of oxygen depletion consistent with the organically enriched sediments, moderate levels of phytoplankton biomass and generally low macroalgal accumulations associated with its observed level of nitrogen enrichment. Oxygen levels were generally greater than 5 mg L^{-1} (95% of record) and did not drop below 4 mg L^{-1} (time series), although infrequent declines below 4 mg L^{-1} were observed in the water quality monitoring program. Chlorophyll levels were moderate to high, averaging 15.3 ug/L and frequently >20 ug/L, however, the Mashpee Water Quality Program found levels averaging 6.3 ug L^{-1} (2000-2010). Overall, the moderate levels of oxygen depletion and moderate chlorophyll-a levels with periodic large phytoplankton blooms, and generally low macroalgae accumulations within the northern basin are consistent with the generally productive benthic animal communities, comprised of transitional species (*Ampelisca*) that colonized its sediments.

The southern portion of the main basin of Waquoit Bay is also showing moderate (to high under algae mat) oxygen stress to benthic communities, with a gradient of less oxygen depletion moving toward the tidal inlet. The bottom waters have large daily excursions in oxygen levels (5-7 mg L^{-1}), more pronounced than in the northern portion. Large daily excursions in oxygen levels are a clear indication of organic enrichment resulting from nitrogen loading and, within the main basin, manifests itself through organic enrichment of sediments, large macroalgal accumulations and phytoplankton biomass. The effect of these responses is to unbalance the water column oxygen cycle through high rates of oxygen input via photosynthesis in daylight and high rates oxygen uptake during darkness. The very large quantities of macroalgae throughout the southern portion of the basin clearly plays a role in the very high daytime oxygen levels which regularly persisted over 10 mg L^{-1} and occasionally exceeded 20 mg L^{-1}. Night time oxygen levels within the mid reach declined below 4 and 3 mg L^{-1} approximately 11% and 5%, with infrequent depletions to less than 1 mg L^{-1} (42 day record). By comparison, near the tidal inlet oxygen depletions were less, declining below 5 mg L-1 for 15% and less than 4 mg L^{-1} for ~3% of the mooring record. The water quality monitoring program observed only levels in the upper reach of the southern basin <5 mg L^{-1} and <4 mg L^{-1} in 20% and 9% of the sampling dates, respectively, with higher oxygen levels near the inlet (all samples > 5 mg L^{-1}).

Chlorophyll-a levels paralleled the oxygen levels within the southern portion of Waquoit Bay. The mid region generally shows only moderately enhanced water column chlorophyll, averaging 7 ug L^{-1} and exceeded 5 and 10 ug L^{-1} for 89% and 6% of the time-series record, respectively. Slightly lower levels were found near the inlet, with chlorophyll values averaging 5.4 ug L^{-1} and exceeded 5 and 10 ug L^{-1} 56% and 2% of the time-series record, respectively. The multi-year water quality monitoring program found a similar pattern with the mid and lower regions having average chlorophyll-a levels of 6.3 ug L^{-1} and 4.5 ug L^{-1}, respectively. Oxygen levels at this location in the lower portion of the main bay show only low to moderate impairment associated with nitrogen enrichment, although these conditions coupled with the macroalgal accumulations have been sufficient to result in the loss of eelgrass coverage throughout almost all of the lower reach of the main basin. It should be noted that conditions at the "inlet" location are the highest quality within the main basin of Waquoit Bay.

The western sub-embayments to the Waquoit Bay Embayment System, Eel Pond and Childs River, exhibit significant summer time oxygen depletion. The upper reaches within Eel Pond and the main channel of the Childs River have significant and frequent oxygen depletion of bottom waters, while the basin of Eel Pond adjacent the tidal inlet shows only moderate levels of oxygen depletion, due to the direct influence of the high quality floodwaters from Vineyard Sound. The upper reach of the Eel Pond and the main channel of the Childs River have regular oxygen depletion (below 5.0 mg/L) during summer, frequent depletions below 4.0 mg/L and periodic depletions to less than 3 mg L^{-1}. In the lower basin of Eel Pond oxygen never declined below 4 mg L^{-1} and was >5 mg L^{-1} for 94% of the 85 day record. The measured oxygen conditions were consistent with the general absence of macroalgae and moderate chlorophyll-a levels in this lower basin. The lower basin is strongly influenced by the nutrient and organic enriched low oxygen waters entering from the upper tidal reaches during out-flowing ebb tides. However, the high turnover of water in lower Eel Pond reduces its ability to build up nutrients, phytoplankton biomass and organic matter, while the inflow of high quality floodwaters from Vineyard Sound results in relatively high water quality for a portion of the flood tide period. The upper portions of the western branch of Eel Pond and the Childs River are clearly presenting significant oxygen stress to benthic animals, while the lower Eel Pond basin presently has a lower level of oxygen stress.

The spatial pattern of oxygen stress parallels chlorophyll-a, indicative of underlying nitrogen enrichment as the ultimate cause of the extent of oxygen depletion. Within the upper portion of Eel Pond and the Childs River, where significant oxygen depletion was observed, chlorophyll-a levels were very high over the entire study period. Within upper Eel Pond large phytoplankton blooms in July and August supported chlorophyll-a levels of over 20 ug L^{-1} (34% of record) and were 40 ug L^{-1} to over 50 ug L^{-1} for about a month. Even after the blooms declined, chlorophyll-a levels remained relatively high at ~10 ug L^{-1}. Similarly, the Childs River also has very high chlorophyll levels, averaging 23.3 ug L^{-1} and rarely dropping below 10 ug L^{-1} and generally between 15 and 40 ug L^{-1}, over the measurement period. In addition, both the upper portion of Eel Pond and the Childs River have regions with accumulations of macroalgae which further contribute to the organic enrichment and enhance bottom water oxygen depletion and further impair benthic animal habitat.

The dissolved oxygen records for the tidally influenced lower Quashnet River and the upper region of Hamblin Pond indicate that these sub-embayments currently maintain a high and moderate level of oxygen stress, respectively. Jehu Pond showed a high level of oxygen depletion, at a level which will impair habitat quality, with dissolved oxygen levels periodically approaching anoxia. Nitrogen enrichment of embayment waters can manifest itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. This phenomenon is best seen in the Quashnet River record, where dissolved oxygen levels frequently become significantly depleted during the night and reach levels in excess of atmospheric saturation during the day time (Figure VII-3). From the oxygen records it is clear that, after Jehu Pond, the Quashnet River has the greatest extent of oxygen depletion. Additionally, the oxygen excursion indicates a high degree of nutrient enrichment (as is supported by the chlorophyll-a data). Note that these data are from the lower part of this system, which has the highest water quality, but still the oxygen levels are <4 mg L^{-1} almost 10% of the time.

Based upon measured total chlorophyll-a pigments (sum of chlorophyll-a and its immediate breakdown product, pheophythin a, as a better indicator of bloom conditions) it is clear that the Quashnet River is highly eutrophic with total chlorophyll-a levels in the upper and mid regions averaging >20 ug L^{-1} (Table VII-4 SMAST data). The moored chlorophyll sensor showed similarly high values (Table VII-5). Phytoplankton blooms appear to be generated within the upper and mid basins of the Quashnet, most likely as a result of the high nitrogen loading to the headwaters via the Quashnet River freshwater discharge. Exceedingly large blooms were observed within the upper Quashnet River basin(>140 ug L^{-1}), with very large blooms (>40 ug L^{-1}) also being observed in the mid reach of the estuary (bridge divides lower from mid reaches). Based upon all of the chlorophyll and oxygen data it appears that the Quashnet River Estuary is showing oxygen stress throughout its reach and it is likely that the level of depletion is higher in the upper and mid reaches than in the lower basin, consistent with the distribution of phytoplankton biomass.

Jehu and Hamblin Ponds support moderate to high total chlorophyll levels, averaging 11.9 and 7.4 ug L^{-1}, respectively. Jehu Pond appears to be showing more nutrient enrichment than Hamblin Pond, both on average and relative to the size of the blooms (Table VII-4, maximum values). The high phytoplankton biomass in Jehu Pond is consistent with the observation of oxygen stress in this system. The moderate total chlorophyll levels in Hamblin Pond are consistent with its moderately good oxygen status. Similarly, Little River and Great River had average total chlorophyll levels of 5-6 ug L^{-1}, as might be expected from the outflow concentrations from their upper basins. The agreement between the chlorophyll land oxygen levels in these Pond basins is likely the result of their physical structure.

The dissolved oxygen and chlorophyll-a data alone indicate a clear pattern of nutrient related habitat quality. At present, the Quashnet River estuary is showing poor oxygen status (based upon depletions, daily excursions, and the mooring in the lower basin) and large phytoplankton blooms. While it appears to be stressed throughout, there is a clear gradient from hyper-eutrophic in the upper regions to eutrophic in the lower basin. Jehu Pond is also showing nitrogen enriched conditions, with periodic hypoxia/anoxia in the basin and high phytoplankton biomass. Hamblin Pond is showing the best nutrient related habitat quality, based both upon its moderately good oxygen conditions and moderate phytoplankton biomass. Based only upon the dissolved oxygen and chlorophyll data the nutrient related habitat quality of the three estuaries to eastern Waquoit Bay can be classified is as follows: Quashnet River estuary - Significantly Impaired, Jehu Pond - Moderately/Significantly Impaired, Hamblin Pond - Moderately Impaired.

Infaunal Communities: Benthic animal indicators were consistent with the levels of oxygen depletion, chlorophyll-a and organic enrichment, including macroalgal accumulation, within all of the sub-embayments of the Waquoit Bay System. The System is presently supporting benthic habitat ranging from minimally/moderately impaired to significantly impaired. It should be noted that, given the loss of eelgrass beds, throughout the main basin of Waquoit Bay, eastern and lower Eel Pond (fringing beds in Childs River), as well as the Quashnet River, Hamblin Pond/Little River and Jehu Pond/Great River, it is clear that the Waquoit Bay Embayment System is clearly impaired by nutrient overloading throughout its tidal reaches.

Based upon the infaunal community survey it appears that most of the Waquoit Bay Embayment System is presently supporting impaired benthic animal habitat, primarily resulting from nitrogen and organic enrichment, periodic oxygen stress and in some areas, accumulations of drift macroalgae that "smother" benthic animals. At present, high quality benthic habitat is only found within the lower basin of Eel Pond and the Seapit River. These areas do not have significant accumulations of macroalgae or oxygen depletion and have relatively oxidized sediments comprised of medium to fine sands with low organic enrichment or consolidated muds. The lower basin of Eel Pond has large tidal flows and access to the high quality waters of Vineyard Sound on the flooding tide and supports benthic animal community that is moderately diverse (H'=2.58) with moderate Evenness (E=0.57), with a moderate to high number of species (23) and large number of individuals (>1000). This basin generally has moderate to high quality benthic habitat, but does have some patches of amphipods mats, indicative of a low to moderate level of impairment. This low to moderate impairment is completely in-line with the low to moderate levels of oxygen stress, organic enrichment and inflows of poor quality waters as the upper basins of Eel Pond and the Childs River enter on ebbing tides. The Seapit River presently shows the highest quality benthic animal habitat within the estuary, supporting a productive community with high numbers of individuals (>1000) and species (33), with high diversity (H'=3.34) and Evenness (E=0.66), comprised of crustaceans, mollusks and polychaetes with some deep burrowers. The eastern branch of Eel Pond, between Seapit River and Eel Pond showed moderate level of habitat quality (lower than Seapit River and the lower basin of Eel Pond) also with high numbers of individuals (>1000), but only moderate numbers of species (18) and moderate diversity (H'=2.37). The slightly greater impairment of this habitat likely results from inputs of high nutrient and organic matter, low oxygen waters entering from the Childs River on each ebbing tide.

In contrast, the upper reach of the western branch of Eel Pond and the Childs River are showing significant impairment of their benthic animal habitat. These basins support low to moderate numbers of species (8-11) and moderate numbers of individuals (~300), with low diversity (H'= 1.48, 1.87) and Evenness (E= 0.50, 0.56) and a community dominated by organic tolerate species, with some stress indicators (Childs River, *Capitella* = 29% of population). The observed benthic communities are consistent with the accumulations of drift macroalgae, high chlorophyll levels (~20 ug L^{-1}) and significant oxygen depletions (<4 mg L^{-1}) with periodic oxygen declines to < 3 mg L^{-1}. Sediments are organic enriched soft muds, frequently covered by accumulations of drift macroalgae.

The main basin of Waquoit Bay also shows a gradient in benthic habitat quality, with the upper northern basin supporting a productive animal community, dominated by transitional species structured primarily as an amphipod mat (*Ampelisca*). The present benthic community consists of a moderate number of species (15) with high numbers of individuals, low numbers stress indicator species, moderate diversity (H'=2.3) and Evenness (E=0.60. Amphipod mats are indicative of a transitional community associated with moderately impaired organic enriched environments, sometimes with some disturbance (e.g. harbors). In contrast, the benthic habitat within the southern portion of the main basin is clearly significantly impaired. Much of the impairment derives from the ubiquitous dense accumulations of drift macroalgae. As a result the community has low to moderate numbers of species (13) with moderate-high numbers of individuals, dominated by crustaceans with some patches of amphipod mats (in open areas); low diversity (H'=2.0) and Evenness (E=0.56). The crustaceans appear to be primarily species that graze on algae or algal mats, with few deep burrowers. Within this basin it appears that organic enrichment is primarily through macroalgae and to a lesser extent phytoplankton. While periodic stressful oxygen levels periodically occur, the oxygen concentrations experienced by benthic animals beneath the macroalgal accumulations are certain to be lower and more stressful than measured. Restoration of benthic habitat in this large basin will require nitrogen management to lower macroalgal production, hence accumulations.

The Quashnet River Estuary is supporting severely degraded benthic habitat consistent with the above oxygen and organic enrichment metrics, with only a single species being found, hence a diversity equal to 0. The severely degraded nature of this habitat is underscored by the virtual absence of an infaunal community with only 18, 4, and 0 individuals being found at the three sites, compared to 100's to 1000's being found at healthy sites. The Jehu Pond and Hamblin Pond systems showed infaunal community habitats ranging from healthy to significantly impaired. There appears to be a gradient in habitat quality within the Jehu Pond/Great River Estuary. The basin of Jehu Pond supported a low number of species (4-6) and total individuals <150 at two of three stations and low diversity at all stations (<1.8). However, the Great River showed markedly better habitat, with 9-10 species and >1000 individuals per sample at each station, and slightly higher diversity. Hamblin Pond/Little River showed a similar pattern, although with much better habitat quality. Only the mid basin of Hamblin Pond was significantly impaired with all of the other stations showing 10-19 species and 500-3200 individuals per sample. Diversity was also high, generally $\geq$2.4. Most likely deposition within the mid basin of Hamblin Pond and subsequent organic matter loading effects are responsible for the observations at this station. However, the other areas of this system appear to support healthy benthic habitat (Lower Hamblin Pond and Little River) or habitat that is only moderately impaired (Upper Hamblin Pond).

Sage Lot Pond is a small salt marsh dominated pond tributary to the lower portion of the southern main basin of Waquoit Bay. As a wetland dominated salt pond, Sage Lot Pond is naturally nutrient and organic matter enriched. The high productivity (individuals >1000) and low species numbers (10) are consistent with this type of ecosystem (but not open water embayments). However, it is clear that even for a salt marsh pond, this system is present supporting impaired benthic habitat due to the dominance of macroalgal associated crustaceans and stress indicator species (*Capitella*, 39% of population).

Overall, the pattern of infaunal habitat quality throughout the Waquoit Bay Embayment System is consistent with measured dissolved oxygen concentrations, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily includes the structure of the specific estuarine basin, specifically as to whether a basin area is wetland influenced or an open water tidal embayment. Based upon this analysis it is clear that most of the benthic animal habitat within the Waquoit Bay Embayment System is moderately to significantly impaired (Quashnet River, severely degraded) by nitrogen and organic matter enrichment, while the moderate to high quality benthic animal habitat is primarily found in the region of the Seapit River down to the Eel Pond inlet. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the significantly impaired basins presently range from 0.65 to 1.20 mg TN L^{-1}, levels typical of other estuarine basins with significant impairment of benthic animal habitat throughout southeastern Massachusetts estuaries.

The results of the assessment of nutrient related habitat quality for each estuary is summarized in Table VIII-1a, b.

Table VIII-1a. Summary of Nutrient Related Habitat Health for the Quashnet River, Hamblin Pond/Little River and Jehu Pond/Great River sub-embayments to the Waquoit Bay System, based upon assessment data presented in Chapter VII.

Health Indicator	Eastern Sub-Embayments of the Waquoit Bay System					
	Quashnet River		Hamblin Pond/Little R.		Jehu Pond/Great R.	
	Upper	Lower	Hamblin Pond	Little River	Jehu Pond	Great River
Dissolved Oxygen	SI	SI	MI	MI	SI	MI
Chlorophyll	SD	SI	MI	MI	MI/SI	MI
Macroalgae	SD	SD	--[2]	--[2]	--[2]	--[2]
Eelgrass	SI/SD	SI/SD[1]	MI	MI	MI	MI
Infaunal Animals	SD	SD	MI	H	SI	MI
Overall:	**SD**	**SI/SD**	**MI**	**H/MI**	**SI**	**MI**

1 – eelgrass lost prior to 1951; 2- sparse to no accumulation;
H = healthy habitat conditions; MI = Moderate Impairment; SI = Significant Impairment;
SD = Severe Degradation

Table VIII-1b. Summary of Nutrient Related Habitat Health for the Waquoit Bay, Eel Pond, Child's River and Sage Lot Pond sub-embayments to the Waquoit Bay System, based upon assessment data presented in Chapter VII. Eel Pond East is Child's River to Inlet.

Health Indicator	Western Sub-Embayments of the Waquoit Bay System					
	Waquoit Bay		Eel Pond		Child's River	Sage Lot Pond
	North	South	West	East		
Dissolved Oxygen	MI[1]	MI/SI[2]	SI[3]	MI[4]	SI[5]	H[6]
Chlorophyll	MI/SI[7]	MI[8]	SI[9]	MI[10]	SI[11]	MI[12]
Macroalgae	MI[13]	SD[14]	SI/SD[15]	MI[16]	MI/SI[17]	SI[18]
Eelgrass	SI[20]	SI[20]	--[19]	SI[20]	SI[20]	MI[21]
Infaunal Animals	MI[22]	SI[23]	SI[24]	MI[25]	SI[26]	MI/SI[27]
Overall:	**SI[28]**	**SI/SD[28,29]**	**SI[30]**	**SI[28,31]**	**SI[28,32]**	**MI[33]**

1 - oxygen depletions generally >5 mg/L 95%, of record MWQMP: <4 mg/L 5% of 34 dates
2- oxygen depletions mid basin: <5 mg/L 24%, <3 mg/L 11% and <3 mg/L 5%of record MWQMP: <4 mg/L 5% of 34 dates; lower basin: <5 mg/L 15%, <4 mg/L 3% of record; MWQMP: always >5 mg/L, >6 mg/L 72% on 34 dates
3- oxygen depletions upper reach: <5 mg/L 41%, <4 mg/L 22% and <3 mg/L 7%of record, MWQMP: <3 mg/L 7% of 34 dates; mid reach MWQMP: <4 mg/L 12%, <3 mg/L 2% of 34 dates
4- oxygen depletions MWQMP upper reach: <5 mg/L 26%, <4 mg/L 10% and <3 mg/L 2%of 34 dates; lower basin near inlet: always >4 mg/L, 4-5 mg/L 6% of 85 day record, MWQMP, >5mg/L 91%, 4-5 mg/L 9% of 34 dates
5- oxygen depletions mid reach: <5 mg/L 38%, <4 mg/L 24%, <3 mg/L 11% of 23 day record, MWQMP <5 mg/L 51%, <4 mg/L 30% and <3 mg/L 6% of 34 dates
6- primarily a salt marsh pond, basin surrounded by extensive tidal saltmarsh resulting in natural organic enrichment WBNERR SWMP mooring: periodically to 2-3 mg/L ~5%, frequently <4 mg/L 11% of record, rarely to1 mg/L oxygen depletions *typical* of salt marsh basins and creeks.
7 - high chlorophyll levels, average = 15.3 ug/L, frequently (18%) >20 ug/L of 22day record; MWQMP: mean 6.3ug/L
8- moderate levels, mid-basin mean = 6.8 ug/L, generally 5-10 ug/L (89%) of 22day record; lower basin mean 5.4 ug/L, <10 ug/L 98% of 42 day record, rarely >10 ug/L; MWQMP: upper basin mean 6.3ug/L; lower basin mean 4.5 ug/L
9- high chlorophyll-a levels upper reach: mean 17.4 ug/L, frequently (34%) >20 ug/L of 72day record; MWQMP: upper and mid reach mean ~20 ug/L of 34 dates;
10- moderate chlorophyll-a levels upper reach: MWQMP mean 7.5 of 34 dates, lower basin mean 6.2 ug/L, generally <10 ug/L (82%) rarely >15 ug/L (2%) of 85day record; MWQMP: lower basin mean 6.6 ug/L of 34 dates;
11- very high chlorophyll-a levels mid reach: mean 23.3 ug/L, >20 ug/L 53% and frequently (37%) >25 ug/L of 23day record; MWQMP: upper and mid reach mean ~28 ug/L of 34 dates;
12- moderate chlorophyll-a from water quality monitoring program
13- sparse ubiquitous *Gracillaria*, with *Codium* in uppermost region, dense accumulations in lowermost reach
14- dense accumulations of *Cladophora* and a variety of branched and filamentous forms, extensive coverage
15- moderate to dense accumulations of branched forms with *Cladophora*, some open areas in upper reach
16- sparse accumulations of branched forms, some attached *Codium*, patches of algal mat covering surface
17- patches of dense *Ulva* and some accumulations of drift branched forms, some algal mat, large open areas
18- accumulations of red branched macroalgae, moderate to high coverage.
19- no evidence this basin is supportive of eelgrass.
20- MassDEP (C. Costello) indicates that eelgrass beds lost from this reach of tidal river between 1951-1995, supported by quantitative time-series analysis by Short & Burdick (1996).
21- small moderate density bed, moderate-heavy epiphytes, macroalgal accumulations and organic sediments.
22- high numbers of individuals, moderate number species (15), low numbers stress indicator species, moderate diversity (H'=2.3) & Evenness (E=0.60, amphipod mats - transitional community organic enrichment species
23- moderate-high number of individuals, low to moderate species (13), dominated by crustaceans, some patches of amphipod mats, community associated with drift algal accumulations, dominated by organic enrichment species; low diversity (2.0) and Evenness (0.56).
24- low-moderate number of individuals, low species (8), low numbers of stress indicator species, some areas with depauperate populations, dominated by organic enrichment species; low diversity (1.5) and Evenness (0.50).
25- high numbers of individuals, moderate number of species (18), low numbers of stress indicator species, moderate diversity (H'=2.4) and Evenness (E=0.57, dominated by amphipod mats - transitional community dominated by organic enrichment species.
26- moderate number of individuals, low species (11), some stress indicator species (*Capitella*), dominated by organic enrichment species (Crustaceans); low-moderate diversity (1.9) and Evenness (0.56).
27- naturally organic enriched salt marsh dominated basin, now showing stress: high numbers of individuals low species (10) mainly crustaceans atypical for salt marsh basins, some stress indicators (Capitella);
28- Significant impairment results from loss of historical eelgrass coverage
29- Severe degradation resulting from dense accumulations of macroalgae, impacting eelgrass re-establishment and benthic animal communities.
30- Significantly Impaired benthic animal habitat, consistent with macroalgal accumulations and periodic low oxygen
31- Benthic animal habitat moderately impaired consistent with DO, chlorophyll-a levels and macroalgal accumulations
32- Benthic animal habitat significantly impaired consistent with DO depletion, high chlorophyll-a levels, organic enrichment of sediments with some areas of dense macroalgal accumulation
33- as a salt marsh dominated basin, it naturally organic and nutrient enriched and is less sensitive to nitrogen loading than open water basins, however, the eelgrass habitat is moderately impaired due to the high occurrence of epiphytes and macroalgal accumulations in this basin.

MWQMP: Mashpee Water Quality Monitoring Program (2000-2010)
H = healthy habitat conditions; MI = Moderate Impairment; SI = Significant Impairment;
SD = Severe Degradation; -- = not applicable to this estuarine reach

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

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

Given the complex configuration and hydrodynamics of the Waquoit Bay Embayment System, multiple nitrogen thresholds locations were selected as to insure an accurate determination of estuarine response to reductions in watershed nitrogen loading and/or enhanced tidal flushing. Eelgrass surveys and analysis of historical data for the Waquoit Bay Embayment System indicated that eelgrass beds, when the watershed was relatively undeveloped (1951), were generally found within each sub-embayment, with the exception of Quashnet River and the western branch of Eel Pond. In contrast, presently virtually all eelgrass has been lost from the Waquoit Bay Embayment System, with the exception of Sage Lot Pond and a possible remnant patch associated with the main tidal inlet. All of the basins with well documented historic eelgrass coverage within this system, which no longer support eelgrass coverage, are classified as significantly impaired relative to eelgrass habitat. Since eelgrass is more sensitive to nitrogen enrichment than benthic animal habitat, restoration of eelgrass in these basins will also restore impairments to benthic habitat as well.

Within the main basin of Waquoit Bay, a sentinel station was selected at the long-term monitoring location (WB12) targeting restoration of eelgrass habitat within the basins northern and southern portions. Similarly, within the Childs River the long term monitoring within the main channel near the upper extent of the historic coverage as selected (CR02). Meeting the nitrogen target at both these stations will necessarily result in lower total nitrogen levels in the down gradient Eel Pond (east branch and Eel Pond lower basin) and southern portion of Waquoit Bay, to restore eelgrass habitat in these lower tidal reaches as well. Meeting the nitrogen threshold in upper Waquoit Bay will also lower nitrogen related impairments in Sage Lot Pond, which is presently supporting moderately impaired eelgrass habitat. As such, Sage Lot Pond is presently just over its nitrogen threshold, and only a moderate reduction in nitrogen levels is required to achieve restoration. Since Sage Lot Pond exchanges tidal waters with the lower portion of Waquoit Bay, as nitrogen levels are reduced in the main basin, Sage Lot Pond levels will decline as well. For these basins, the target nitrogen level to achieve restoration of eelgrass habitat is 0.38 mg TN L^{-1}, compared to the present tidally averaged TN levels of 0.40 mg TN $L^{-1}$for Waquoit Bay and 0.63 mg TN $L^{-1}$for the Childs River station.

The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel locations within Waquoit Bay and Child River basins of 0.38 mg TN L^{-1} is based upon comparison to other local embayments of similar depths and structure under MEP analysis, as there are is no high quality eelgrass habitat presently with this System. A well studied eelgrass bed within the lower Oyster River (Chatham) has been stable at a tidally averaged water column TN of 0.37 mg TN L^{-1}, while eelgrass was lost within the Lower Centerville River at a tidally averaged TN of 0.395 mg TN L^{-1}, and also within Waquoit Bay itself at 0.39 mg TN L^{-1}. The nitrogen threshold for the lower main basin of Popponesset Bay and Lewis Bay and for the complex Stage Harbor System was 0.38 mg TN L^{-1}. These latter 3 systems have a similar complex multiple component structure to the Waquoit Bay System. Consistent with these threshold levels, eelgrass beds still exist within Hyannis Harbor at tidally averaged nitrogen levels of 0.37 mg TN L^{-1}, similar to that in the Oyster River (Chatham). More stringent nitrogen thresholds (0.35 mg TN L^{-1}) have been determined for the deeper waters of Phinneys Harbor and West Falmouth Harbor estuaries where detailed eelgrass/nitrogen analysis was available. These site specific data indicate that the threshold for eelgrass in this system is between 0.370 and 0.393 (or 0.385) mg TN L^{-1}, tidally averaged TN. Strong support for the 0.380 mg TN L^{-1} value determined for the sentinel locations (WB12, CR02).

Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fisheries resources), benthic infaunal habitat quality must also be supported as a secondary condition. This is the case for the western basin of Eel Pond which has not historically supported eelgrass beds, but presently has significantly impaired benthic animal habitat (and the Quashnet River described below). Benthic animals are more tolerant of nutrient and organic matter enrichment than eelgrass, which requires clear waters and high oxygen levels. At present, in the regions with moderately to significantly impaired infaunal habitat within upper Eel Pond, long term monitoring station ER01), has an average tidal total nitrogen (TN) level of 0.67 mg TN L^{-1}. The observed impairments throughout this estuary are consistent with observations by the MEP Technical Team in other estuaries along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg TN L^{-1} were found to be supportive of healthy infaunal habitat and where moderately impaired habitat was found at ~0.6 mg TN L^{-1}. Similarly, moderate impairment was also observed at TN levels (0.535-0.600 mg TN L^{-1}) within the Wareham River Estuary, while the Centerville River system showed moderate impairment at tidally averaged TN levels of 0.526 mg TN L^{-1} in Scudder Bay and at 0.543 mg TN L^{-1} in the deep middle reach of the Centerville River. Based upon these observations, the MEP Technical Team concluded that an upper limit of ≤0.50 mg TN L^{-1} tidally averaged TN at the threshold station (ER01) would result in healthy infaunal habitat throughout the western branch of Eel Pond.

Within the Quashnet River, Hamblin Pond/Little River and Jehu Pond/Great River Estuaries within the Waquoit Bay System, it was necessary to select 3 sentinel locations. The Quashnet River Estuary operates independent from the Hamblin Pond and Jehu Pond Estuaries, except as they share common source waters from Waquoit Bay. Their interaction is primarily through their effect on the nitrogen level with Waquoit Bay. The sentinel system within the Quashnet River Estuary was set within the upper/mid basin (region above the bridge). Achieving the nitrogen threshold at this station will also improve benthic habitat in the lower basin. Since there is no historical evidence that the Quashnet River Estuary supported eelgrass, the threshold nitrogen concentration was based upon restoring benthic habitat at the sentinel station. The target nitrogen concentration to restore infaunal habitat is based upon the high quality infaunal sites in lower Hamblin Pond and in Little River (Stations 176 and 170, Figure VII-9). The tidally averaged nitrogen levels at these sites are 0.498 and 0.524 mg TN L^{-1}, respectively. These values are consistent with the infaunal guidance levels within the Popponesset Bay sub-embayments of 0.5 to 0.4 mg TN L^{-1} (0.5 mg TN L^{-1}) being the upper threshold value). Based upon these data a conservative estimate for the infaunal threshold for the Quashnet River Estuary is 0.50 mg TN L^{-1}, with 0.52 likely to represent a slight stress, but still high quality habitat.

Within the Hamblin Pond/Little River and Jehu Pond/Great River Estuaries the sentinel locations were placed within the pond basins. The target nitrogen threshold focuses on eelgrass restoration of these systems. Given the nitrogen gradients, with the ponds having the highest nitrogen levels within their respective estuarine sub-embayment, achieving the nitrogen target in the ponds will necessarily result in high quality habitat in the down-gradient reaches.

However, setting the threshold for these ponds is not straight-forward. In other systems, a target nitrogen level of 0.38 mg TN L^{-1}has been supported by the on-site data and assessments. It appears that this level would be restorative of eelgrass in the Jehu Pond and Hamblin Pond estuaries, as the few diminishing eelgrass patches in the main basin of Waquoit Bay, near the inlet persist at 0.395 mg TN L^{-1}, relatively consistent with this threshold. A threshold of 0.38 mg TN $L^{-1}$is being evaluated for the main basin of Waquoit Bay and will be thoroughly addressed when the whole of the system is re-addressed by MEP. However, eelgrass was almost completely lost from the main basin prior to significant loss from the Hamblin Pond and Jehu Pond Estuaries in the 1980's (Figures VII-24, VII-25 and VII-26). Therefore, another approach to developing the threshold nitrogen level for these Ponds relates to the nitrogen level in the main bay, which is also their source water (boundary condition). Based upon a main bay boundary condition of 0.38 mg TN L^{-1} (upper eelgrass threshold) the nitrogen levels in the Ponds would necessarily have been >0.38 mg TN L^{-1}, given the gradients established by the interplay of loading and hydrodynamics. This is consistent with the existence of a few diminishing small patches of eelgrass at nitrogen levels on the order of 0.5 mg TN L^{-1} in these ponds in 2001-2003. Note that since eelgrass can persist at nitrogen levels that are non-supportive of healthy beds, a value of 0.5 mg TN L^{-1} is beyond the supportive nitrogen threshold.

To refine the nitrogen threshold for Jehu and Hamblin Ponds, modeling was conducted. The goal of this effort was to reconcile nitrogen levels to historical shifts in eelgrass distribution. The concept was to use conservative estimates of nitrogen loads and concentrations to estimate nitrogen levels prior to the eelgrass loss in the main bay and ponds. The details of the assumptions and modeling are presented in Section VIII.3. Based upon the modeling it appears that Jehu Pond could support eelgrass at a nitrogen threshold of 0.446 mg TN L^{-1}. This is above the 0.38 mg TN L^{-1} threshold likely for the main bay (and utilized for Stage Harbor and Popponesset Bay), but lower than the 0.527-0.552 found in the Bassing Harbor System. This level for Jehu Pond is also consistent with the pattern and timing of eelgrass loss throughout the Waquoit Bay System. Although Hamblin Pond is similar to Jehu Pond in gross structure, it has very different loading and attenuation characteristics. The result is that the structure of the system produces much lower nitrogen levels so a threshold of 0.38 mg TN L^{-1} was selected to allow for uncertainties.

As will be discussed below, it will not be possible to achieve the target nitrogen levels for the Quashnet River, Hamblin Pond/Little River or Jehu Pond/Great River Estuary without lowering the nitrogen level within the main basin of Waquoit Bay. At present the flooding waters from Waquoit Bay are sufficiently nitrogen enriched that even modest nitrogen loads from the watersheds to these estuaries exceed nitrogen targets. In fact, the flood waters from the main basin currently exceed the 0.38 mg TN L^{-1}.

VIII.3 DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Waquoit Bay 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 Waquoit Bay. 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 present septic and total watershed loading and the loadings for the two modeled threshold scenarios is provided in Tables VIII-2 and VIII-3.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required more than 75% 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 60% of the septic load from the west branch of Eel Pond watershed results in a 46% 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.

It was required to remove more load from Hamblin Pond than what was estimated in the earlier technical report that the existing TMDL for this system is based. This is because those earlier models utilized an unvarying boundary condition concentration. This was a necessary simplification at the time that this earlier analysis was performed.

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 Nantucket Sound, 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 stations is shown in Table VIII-4. To achieve the threshold nitrogen concentrations at the sentinel stations, reductions in TN concentrations of typically greater than 45% are required in the system. Table VIII-5 presents the comparison of present concentrations to threshold concentrations at the sentinel stations.

Although the above modeling results provide one manner of achieving the selected threshold level for the sentinel sites 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 nitrogen remediation effort 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 reduce the load that finally reaches the estuary. Presently, this attenuation is occurring in surface water inputs to the system (e.g., Moonakis/Upper Quashnet River) due to natural ecosystem processes and the extent of attenuation being determined by the mass of nitrogen which discharges to these systems. Future nitrogen management should take advantage of natural nitrogen attenuation, where possible, to ensure the most cost-effective nitrogen reduction strategies. However, “planned” use of natural systems has to be done carefully and with the full analysis to ensure that degradation of these systems will not occur. One clear finding of the MEP has been the need for analysis of the potential associated with restored wetlands or ecologically engineered ponds/wetlands to enhance nitrogen attenuation. Attenuation by ponds in agricultural systems has also been found to work in some cranberry bog systems, as well. Cranberry bogs, other freshwater wetland resources, and freshwater ponds provide opportunities for enhancing natural attenuation of their nitrogen loads. Restoration or enhancement of wetlands and ponds associated with the lower ends of rivers and/or streams discharging to estuaries are seen as providing a dual service of lowering infrastructure costs associated with wastewater management and increasing aquatic resources associated within the watershed and upper estuarine reaches.

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the Waquoit 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
Waquoit Bay	1.397	1.397	+0.0%
Childs River - upper	9.929	1.986	-80.0%
Eel Pond - east branch	1.688	0.338	-80.0%
Eel Pond - south basin	0.458	0.458	+0.0%
Eel Pond - west branch	12.548	5.019	-60.0%
Quashnet River	1.904	0.628	-67.0%
Hamblin Pond	3.427	0.000	-100.0%
Little River	0.885	0.000	-100.0%
Jehu Pond	2.888	0.000	-100.0%
Great River	2.674	0.000	-100.0%
Sage Lot Pond	1.132	0.000	-100.0%
Childs River - freshwater	8.134	1.627	-80.0%
Moonakis River (upper Quashnet)	10.504	3.466	-67.0%
Red Brook -freshwater	6.575	0.658	-90.0%
Total	64.142	15.576	-75.7%

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Waquoit Bay	2.088	2.088	0.0%
Childs River - upper	12.019	4.076	-66.1%
Eel Pond - east branch	2.170	0.820	-62.2%
Eel Pond - south basin	0.523	0.523	0.0%
Eel Pond - west branch	16.337	8.808	-46.1%
Quashnet River	2.773	1.497	-46.0%
Hamblin Pond	4.381	0.953	-78.2%
Little River	1.096	0.211	-80.8%
Jehu Pond	3.912	1.025	-73.8%
Great River	3.671	0.997	-72.8%
Sage Lot Pond	2.753	1.622	-41.1%
Childs River - freshwater	10.622	4.115	-61.3%
Moonakis River (upper Quashnet)	20.507	13.469	-34.3%
Red Brook -freshwater	8.014	2.096	-73.8%
Total	90.866	42.300	-53.4%

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Waquoit Bay	2.088	11.956	-56.779
Childs River - upper	4.076	0.455	-4.291
Eel Pond - east branch	0.820	1.011	19.480
Eel Pond - south basin	0.523	0.663	-4.632
Eel Pond - west branch	8.808	0.890	-2.900
Quashnet River	1.497	0.252	9.496
Hamblin Pond	0.953	1.529	5.712
Little River	0.211	0.156	2.554
Jehu Pond	1.025	0.674	6.897
Great River	0.997	1.307	14.222
Sage Lot Pond	1.622	0.471	-2.726
Childs River - freshwater	4.115	-	-
Moonakis River (upper Quashnet)	13.469	-	-
Red Brook -freshwater	2.096	-	-
Total	42.300	19.364	-12.967

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change above background concentration offshore Waquoit Bay (0.28mg/L), for the Waquoit Bay system. The threshold stations are shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Seapit River	WB11	0.383	0.321	-59.5%
Waquoit Bay - upper basin	**WB12**	**0.402**	**0.327**	**-61.0%**
Waquoit Bay - lower basin	WB13	0.303	0.289	-55.3%
Childs River - upper	CR01	1.146	0.494	-75.2%
Childs River - middle	**CR02**	**0.651**	**0.374**	**-74.6%**
Childs River - lower	CR03	0.342	0.307	-55.8%
Eel River - upper	**ER01**	**0.669**	**0.486**	**-47.1%**
Eel River - middle	ER02	0.428	0.356	-48.7%
Eel Pond	ER03	0.307	0.293	-51.3%

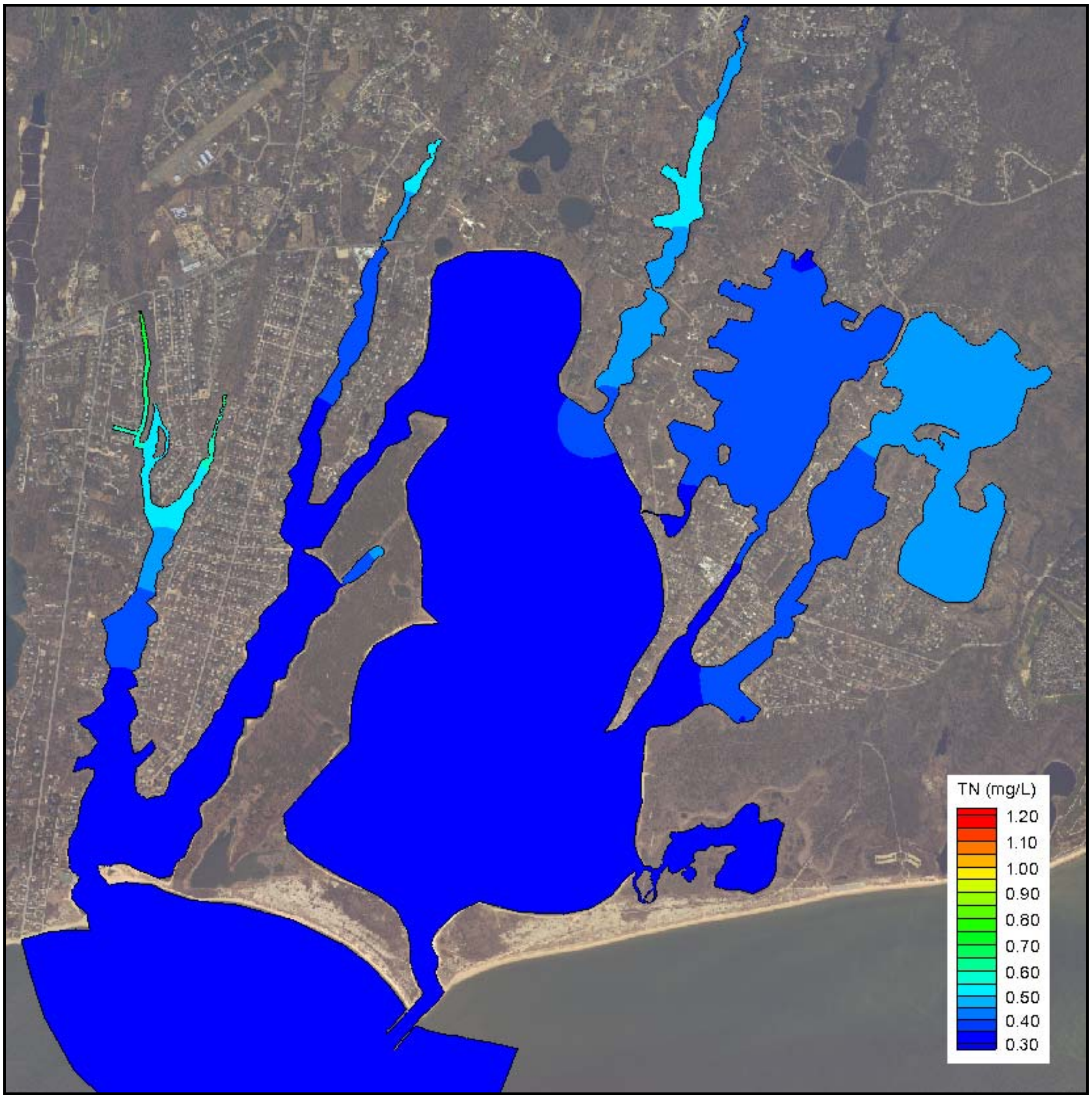


Figure VIII-1. Contour plot of tidally averaged modeled total nitrogen concentrations (mg/L) in the Waquoit Bay estuarine system, for threshold.

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