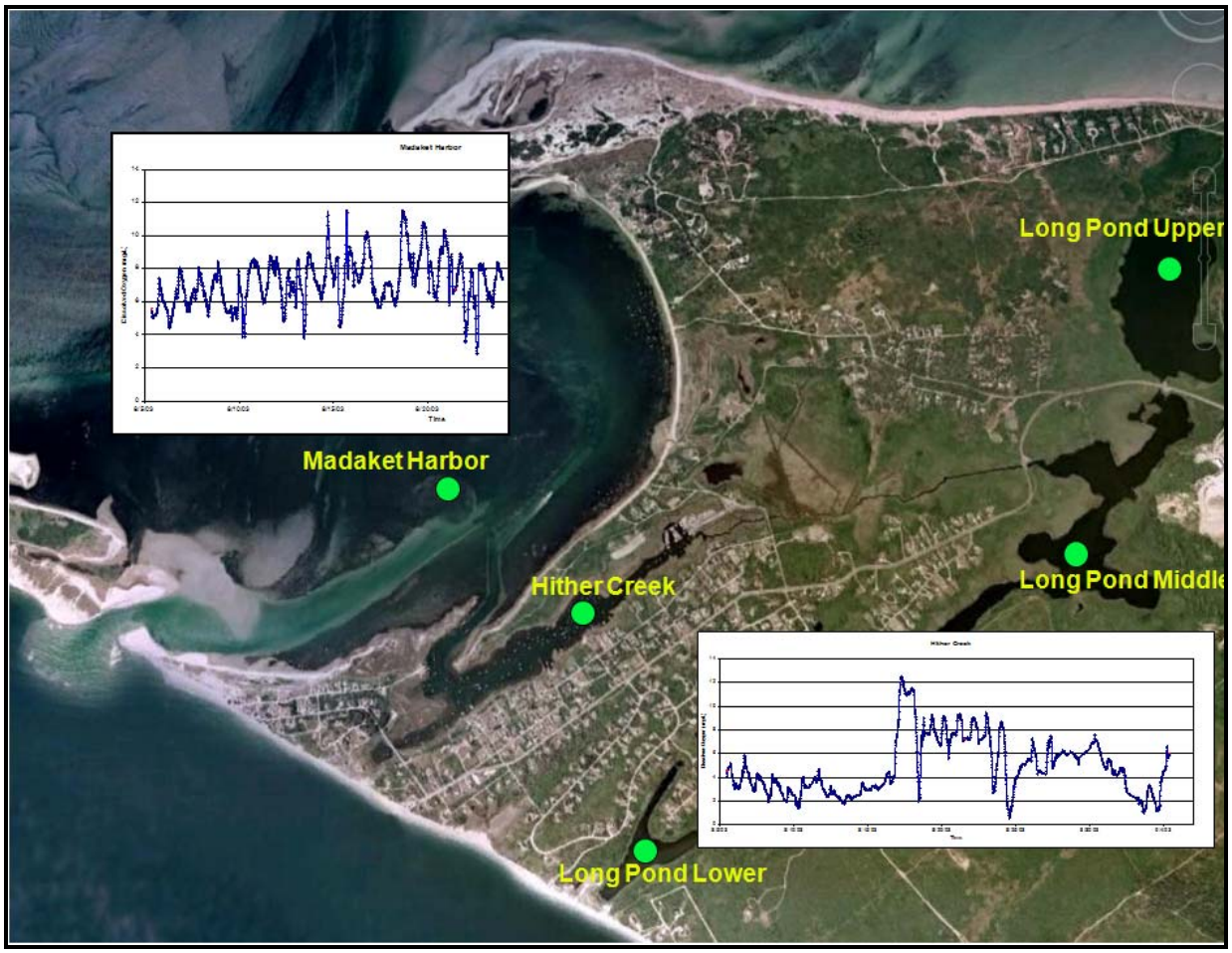
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Madaket Harbor and Long Pond Estuarine System, Town of Nantucket, MA



University of Massachusetts Dartmouth
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Environmental Protection

FINAL REPORT – November 2010

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

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 Madaket Harbor / Long Pond embayment system within the Town of Nantucket is at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater from the increasingly developed watershed to this coastal system. Eutrophication is a process that occurs naturally and gradually over a period of tens or hundreds of years. However, human-related (anthropogenic) sources of nitrogen may be introduced into ecosystems at an accelerated rate that cannot be easily absorbed, resulting in a phenomenon known as cultural eutrophication. In both marine and freshwater systems, cultural eutrophication results in degraded water quality, adverse impacts to ecosystems, and limits on the use of water resources.

The relatively pristine nature of Nantucket's nearshore and Harbor waters has historically been a valuable asset to the island. However, concern over the potential degradation of Harbor water quality began to arise, which resulted in monitoring, scientific investigations and management planning which continues to this day. Madaket Harbor is one of the largest enclosed bays in southeastern Massachusetts and one of the few with a relatively high water quality capable of supporting significant high quality ecological habitats, such as eelgrass beds. Ironically, it is the pristine nature of this system which may indirectly threaten its ecological health as the coastal waters throughout Southeastern New England become increasingly degraded and the pressure for access and development of remaining high quality environments increases. The Town of Nantucket and work groups have long ago recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making, alternatives analysis and ultimately, habitat protection. 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 Town. 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.mass.gov/dep/water/resources/coastalr.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.mass.gov/dep/water/resources/coastalr.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.mass.gov/dep/water/resources/coastalr.htm.

Application of MEP Approach: The Linked Model was applied to the Madaket Harbor / Long Pond embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Nantucket Marine Department, with technical guidance from the Coastal Systems Program at SMAST (see Section II). Evaluation of upland nitrogen loading was conducted by the MEP. Estuaries Project staff obtained digital parcel and tax assessors data from the Town of Nantucket Geographic Information Systems Department, watershed specific water use data from the Wannacomet Water Company (WWC) and watershed boundaries adopted by the town as the Harbor Watershed Protection District (http://www.nantucket-ma.gov). During the development of the Nantucket Water Resources Management Plan, an island-wide groundwater mapping project, using many of the USGS wells on the Island, was completed to characterize the water table configuration of Nantucket (Horsley, Whittan, Hegeman, 1990). Estuary watershed delineations completed in areas with relatively transmissive sand and gravel deposits, like most of Cape Cod and the Islands, have shown that 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). This approach was used by Horsley, Whittan and Hegeman, Inc. (HWH) to complete a watershed delineation for Madaket Harbor (Section III); this watershed delineation was been largely confirmed by subsequent water table characterizations (*e.g*., Lurbano, 2001, Gardner and Vogel, 2005). MEP staff compared the HWH Harbor watershed to a 2004 aerial base map. This comparison found some slight discrepancies likely based on a better characterization of the shoreline; changes were made based on best professional judgment and watershed/water table characterization experience in similar geologic settings. The watershed to Madaket Harbor has been adopted in the town zoning bylaws as the Madaket Harbor Watershed Protection District. (http://www.nantucket-ma.gov/Pages/NantucketMA_IT/gismapsfolder/madaketharborwpd.pdf).

The land-use data obtained from the Town was used to determine watershed nitrogen loads within the Madaket Harbor embayment system and each of the systems sub-embayments as appropriate (current and build-out loads are summarized in Section IV). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Madaket Harbor / Long Pond 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 Nantucket Sound source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Madaket Harbor / Long Pond embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the embayments.

MEP Nitrogen Thresholds Analysis: The threshold nitrogen level for an embayment represents the average water column concentration of nitrogen that will support the habitat quality being sought. The water column nitrogen level is ultimately controlled by the watershed nitrogen load and the nitrogen concentration in the inflowing tidal waters (boundary condition). The water column nitrogen concentration is modified by the extent of sediment regeneration. Threshold nitrogen levels for the embayment systems in this study were developed to restore or maintain SA waters or high habitat quality. High habitat quality was defined as supportive of eelgrass and infaunal communities. Dissolved oxygen and chlorophyll a were also considered in the assessment.

The nitrogen thresholds developed in Section VIII-2 were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Madaket Harbor / Long Pond system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel station chosen for the Madaket Harbor system. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for protection/restoration of this nitrogen threatened 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 Madaket Harbor / Long Pond embayment system in the Town of Nantucket. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. 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 septic system nitrogen loads generally represent 58% of the controllable watershed load to the Madaket Harbor embayment system and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through this source is a good gauge of the feasibility for protection/restoration of the system. Additionally, an alternative scenario was completed which focused on the elimination of nitrogen loads to the Long Pond portion of the embayment system as that source represents 24% of the controllable watershed load to the

Madaket Harbor embayment system and is also more manageable than other of the nitrogen sources.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Madaket Harbor / Long Pond system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. The Madaket Harbor-Long Pond Embayment System is a complex estuary with full tidal marine basins (Madaket Harbor, Hither Creek) connected via Madaket Ditch to tidally restricted brackish water basins (Long Pond, North Head Long Pond) that have significant wetland influence.

Each of type of functional component (salt marsh basin, embayment, tidal river, deep basin (sometimes drown kettles), shallow basin, etc.) has a different natural sensitivity to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of the specific type of basin and the ability to support eelgrass beds and the types of infaunal communities that they support. At present, some of the component basins within the Madaket Harbor-Long Pond Estuary are showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Section VII), indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

Overall, the large open water semi-enclosed main basin of Madaket Harbor is presently supporting high quality eelgrass habitat and productive benthic animal communities. Oxygen generally shows little depletion and chlorophyll a levels were consistently low. It is clear that the open nature of this basin and its relatively small watershed have resulted in only a low level of nitrogen enrichment and high quality habitat. In contrast, the enclosed basin of Hither Creek is presently nitrogen enriched, with high chlorophyll levels and periodic hypoxia (low oxygen). Habitat impairment is clear from the loss of previously existing eelgrass beds and the near absence of benthic animals in the upper reaches. The brackish basins of Long Pond and North Head of Long Pond are also nitrogen enriched beyond their assimilative capacity, but given the natural nutrient and organic matter enrichment of wetland influenced tidal basins their level of impairment is only moderate. There is no evidence that eelgrass habitat has existed previously in these basins, so the present absence does not indicate impairment of this habitat.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate only slightly nutrient enriched conditions within Madaket Harbor and moderate to significant impairment of the enclosed component basins. However, the degree of enrichment and subsequent effect on habitat quality varied widely between these impaired sub-basins.

Madaket Harbor, which functions as a open marine basin generally has only moderate declines in oxygen, moderate amounts of phytoplankton biomass (chlorophyll a), and a low level of nitrogen enrichment (tidally averaged TN <0.33 mg L^{-1}), all factors consistent with its high quality eelgrass habitat. In contrast, Hither Creek's oxygen and chlorophyll a levels indicate a nitrogen and organic matter enriched basin with oxygen frequently declining below 4 mg L^{-1} and 3 mg L^{-1}. Chlorophyll a levels were also significantly elevated. These elevated levels of phytoplankton are consistent with the observed periodic bottom water hypoxia and organic rich soft sediments of the basin. The periodic hypoxia, elevated chlorophyll levels and sediment characteristics are consistent with a nitrogen enriched basin with significantly impaired eelgrass

habitat. The oxygen and chlorophyll a data further support the conclusion that Hither Creek habitats are likely presently impaired by nitrogen enrichment.

Long Pond is a tidally restricted brackish pond dominated by fringing wetlands. Oxygen depletion is large and frequent, generally following the diurnal light/dark cycle. Oxygen frequently declined to <2 mg L^{-1}, with a large daily excursion frequently rising to 2-3 times air equilibration. Although natural wetland channels periodically are hypoxic/anoxic at night, the large daily oxygen excursions are atypical and indicate impairment. Consistent with the oxygen levels, chlorophyll a levels were also very high. The oxygen and chlorophyll a data indicate that while the middle portion of Long Pond is a wetland dominated basin and therefore naturally nutrient and organic matter enriched, the large phytoplankton blooms coupled with the large oxygen excursions suggest that it is currently beyond its nutrient assimilative capacity. The southern tidal reach of Long Pond is less nutrient enriched and shows a lower degree of habitat impairment. While Long Pond, overall, has significant wetland influence and therefore is naturally enriched in nutrients and organic matter the chlorophyll a and to a lesser extent oxygen records indicate that this lower basin is also beyond its nutrient assimilative capacity.

Overall, the oxygen and chlorophyll a levels within the Madaket Harbor - Long Pond System indicate little to no impairment of the outer harbor consistent with its low level of nitrogen enrichment. In contrast, Hither Creek which receives high quality waters on the flooding tide from Madaket Harbor, but nutrient and organic matter enrichment from its watershed inputs and from the upper estuarine reaches via Madaket Ditch, has oxygen declines and chlorophyll levels consistent with its tidally averaged TN of 0.51 mg L^{-1} (Section VI), indicating nitrogen related habitat impairment. Long Pond and North Head of Long Pond are brackish wetland influenced systems that are naturally enriched with nutrients and organic matter. The North Head of Long Pond supported generally high oxygen conditions and moderate chlorophyll a levels at a high tidally averaged TN (0.89 mg L^{-1}). Based upon the function type of this basin, the oxygen and chlorophyll a levels are indicative of high quality to possibly slightly impaired habitat. In contrast, the wetland dominated Long Pond basin is presently showing wide oxygen excursions, frequent hypoxia/anoxia and very high chlorophyll levels indicating that even this naturally enriched system is receiving external nitrogen loading that is resulting in habitat impairments.

The survey of infauna communities throughout the Madaket Harbor-Long Pond Estuary indicated a system presently supporting impaired benthic infaunal habitat in its enclosed component sub-basins (Hither Creek, Long Pond, North Head of Long Pond).

A wide range of benthic animal habitat quality exists within the Madaket Harbor-Long Pond Embayment System. The highest quality infauna habitat was found throughout the main basin of Madaket Harbor that also presently supports extensive eelgrass beds and sustains high oxygen levels and low chlorophyll levels, consistent with its low level of nitrogen enrichment. In contrast, Hither Creek has low numbers of individuals, species and diversity and is dominated by organic enrichment tolerant species (Capitellids). The upper reach of Hither Creek (between water quality monitoring sites MAD 9 & 10) did not support any significant infaunal habitat. The observed impaired infauna habitat is consistent with the observed oxygen and chlorophyll levels in this basin. Long Pond and North Head of Long Pond are brackish water basins with significant wetland influence. As such, these basins are naturally nutrient and organic matter enriched, and assessment of infaunal habitat accounted for their functional types. Overall, these brackish basins presently support productive benthic animal communities. Long Pond supports high numbers of individuals, but low species numbers, diversity and Evenness. The low numbers of total species and overall diversity indicate an impaired habitat consistent with

the observed hypoxic conditions and elevated chlorophyll levels. The North Head of Long Pond is similar to Long Pond with lower numbers of individuals, but the community is dominated by amphipods rather than oligochaeta worms, indicative of a productive organic rich habitat and consistent with the observed oxygen levels in this basin.

At present, eelgrass coverage is extensive and stable throughout the main portion of Madaket Harbor. The existing beds have increased significantly relative to the estimate from 1951. The temporal pattern of eelgrass coverage in Hither Creek clearly indicates that the eelgrass habitat within this basin is presently significantly impaired. In 1951, eelgrass beds covered much of the main basin of the Creek. However, by 1995 the beds had been significantly reduced and limited to the margins of the basin and eelgrass was not found in the 2001 and 2006 MassDEP surveys or the MEP 2003 observations. The recent loss of the 1995 beds coupled with measured periodic hypoxia and high chlorophyll a levels supports the contention that nitrogen enrichment caused the decline in eelgrass habitat. Deepening the basin does impact the ability to restore eelgrass in this basin to 1951 coverage, since the basin is now deeper and depositional. In its present basin configuration, restoration of the eelgrass habitat in Hither Creek, should focus on restoration of the fringing beds in the shallower margins of the basin to the inland extent of the 1951 coverage (water quality station, M11).

In contrast to Madaket Harbor and Hither Creek, the Long Pond basins do not appear to have eelgrass habitat, as there is not present or historical evidence of eelgrass within these basins. Management of nitrogen levels through reduction in watershed nitrogen inputs or increased tidal flushing, as appropriate, is required for restoration of eelgrass and infaunal habitats within the Madaket Harbor-Long Pond Embayment System.

3. Conclusions of the Analysis

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

Threshold nitrogen levels for this embayment system were developed to restore or maintain SA waters or high habitat quality. In this system, high habitat quality was defined as 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 Nantucket, Madaket Harbor / Long Pond embayment system was comprised primarily of runoff from impervious surfaces, fertilizers and wastewater nitrogen. Land-use and wastewater analysis found that generally about 58% 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 cannot be applied to Massachusetts' estuaries, based upon the results of the Great, Green and Bournes Pond Systems, Popponesset Bay System, the Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay and the analysis of the adjacent Nantucket Harbor and Sesechacha Pond systems on the Island of Nantucket. This is almost certainly going to be true for the other embayments within the MEP area, as well as Madaket Harbor and Long Pond.

The threshold nitrogen levels for the Madaket Harbor / Long Pond embayment system in Nantucket were determined as follows:

Madaket Harbor / Long Pond Threshold Nitrogen Concentrations:

- Following the MEP protocol, the restoration target for the Madaket Harbor / Long Pond system should reflect both recent pre-degradation habitat quality and be reasonably achievable. Determination of the critical nitrogen threshold for maintaining high quality habitat within the Madaket Harbor Estuarine System is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. Given the information on a variety of key habitat and basin characteristics, it is possible to develop a site-specific threshold at a sentinel location within the embayment. 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, which is a refinement upon more generalized threshold analyses frequently employed. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of the specific type of basin and the ability to support eelgrass beds and the types of infaunal communities that they support. At present, some of the component basins within the Madaket Harbor-Long Pond Estuary are showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Section VII), indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

- Overall, the large open water semi-enclosed main basin of Madaket Harbor is presently supporting high quality eelgrass habitat and productive benthic animal communities. Oxygen generally shows little depletion and chlorophyll a levels were consistently low, with only very sparse macroalgal abundance.

- The enclosed basin of Hither Creek is presently nitrogen enriched with a tidally averaged TN of 0.51 mg N L^{-1} compared to 0.33 mg N L-1 in Madaket Harbor. The result is high chlorophyll levels and periodic hypoxia (low oxygen), complete loss of eelgrass habitat and regions of dense accumulations of drift macroalgae. In addition, the benthic animal habitat is impaired and nearly absent in much of the northern tidal basin. While nitrogen management needs to target eelgrass restoration in this basin, it will also restore benthic animal habitat, as benthic communities are generally more tolerant of nitrogen enrichment effects than is eelgrass.

- The brackish basins of Long Pond and North Head of Long Pond are also nitrogen enriched beyond their assimilative capacity, but given the natural nutrient and organic matter enrichment of wetland influenced tidal basins their level of impairment is only moderate. TN levels are elevated in these basins, 0.85 - 1.05 mg N L-1, typical of wetland basins and tidal creeks. However, some impairment of habitat presently exists, seen primarily in the high chlorophyll levels and periodic blooms and structure of the benthic animal community. There is no evidence that eelgrass habitat has existed previously in these basins, so the present absence does not indicate impairment of this habitat.

- The decline in eelgrass within Hither Creek makes restoration of eelgrass the target for TMDL development by MassDEP and the primary focus of threshold development for

this system. Additionally, restoration of the basins with impaired benthic animal habitat is also required. However, given the level of impairment in the brackish basins and the goal of restoring eelgrass in Hither Creek, it is certain that nitrogen management to restore eelgrass habitat within Hither Creek the will also result in restoration of the impaired infaunal habitat, as nitrogen enrichment will be significantly reduced to the overall estuary. As such, it appears that the appropriate sentinel station for the Madaket Harbor-Long Pond Embayment System should be located at the northern most extent of the 1951 eelgrass coverage in Hither Creek, which coincides with the baseline Nantucket Water Quality Monitoring Station, M11. To achieve the restoration target of restoring the fringing eelgrass beds in Hither Creek requires lowering the level of nitrogen enrichment. Within Madaket Harbor the basin-wide tidally averaged TN is presently <0.33 mg N L-1, and the basin is supporting high quality eelgrass and benthic infaunal habitat. However, Madaket Harbor eelgrass coverage includes areas in deeper water than that of the location of the fringing eelgrass beds to be restored in Hither Creek (< 1 m) and so a higher level of nitrogen is appropriate for restoration in Hither Creek.

- In shallow systems like the restoration area in Hither Creek, eelgrass beds are sustainable at higher TN (higher chlorophyll a) levels than in deeper waters, because of the "thinner" water column that light has to pass through to support eelgrass growth (less water to penetrate). Therefore to restore eelgrass habitat in Hither Creek the nitrogen concentration (tidally averaged TN) at the sentinel location needs to be between 0.48 and 0.43 mg TN L^{-1}. A threshold of 0.45 mg TN L^{-1} was determined to be appropriate for the Hither Creek sentinel station to restore eelgrass (and infaunal habitat) within this basin.

- It should be noted that as the benthic habitats in the brackish components (Long Pond and the North Head of Long Pond) of the overall system are naturally nitrogen enriched, a moderate reduction in nitrogen levels should be sufficient to restore the benthic habitat. In tidal wetlands the nitrogen levels between 1 and 2 mg N L^{-1} are associated with unimpaired habitat. This is consistent with the only slight impairment of the North Head of Long Pond at TN levels of 0.894 mg L^{-1} and the moderately impaired benthic habitat in Long Pond at a basin averaged TN (tidally averaged) of 0.939 mg N L^{-1}. Given the observed level of impairment in these brackish basins and the frequent association of high quality benthic habitat in wetland influenced tidal channels at 1 mg N L-1, a threshold of 0.8 mg N L-1 is appropriate as the average basin TN level to be supportive of benthic animal habitat. This is a secondary threshold and one that should be met as nitrogen management options are implemented to meet the nitrogen threshold at the down-gradient sentinel station in Hither Creek.

It is important to note that the analysis of future nitrogen loading to the Madaket Harbor / Long Pond estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that 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 Madaket Harbor / Long Pond estuarine system is that protection/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 Madaket Harbor and Long Pond estuary system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. (mg/L)
SYSTEMS										
Madaket Bay	0.238	0.279	0.384	--	0.663	8.603	17.952	27.218	0.34-0.42	--
Hither Creek	0.425	1.134	2.907	--	4.041	0.534	-0.583	3.992	0.58-0.78	--
Madaket Ditch	0.507	0.923	1.510	--	2.433	-	0.061	2.494	--	--
Long Pond	0.142	2.888	0.342	--	3.230	0.975	3.065	7.270	0.24-0.40	
System Total	**1.457**	**5.392**	**5.214**	**--**	**10.605**	**10.805**	**21.490**	**42.901**	**--**	**0.45[8]**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings
[5] atmospheric deposition to embayment surface only
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 2001 – 2008 data, ranges show the upper to lower regions (highest-lowest) of an sub-embayment. Individual yearly means and standard deviations in Table VI-1.
[8] Threshold for sentinel site located in Hither Creek at water quality station M-11

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Madaket Harbor and Long Pond estuary system, Town of Madaket, Massachusetts.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
SYSTEMS						
Madaket Bay	0.663	0.663	8.603	17.952	27.22	0.00%
Hither Creek	4.041	1.134	0.534	-0.583	1.09	-71.94%
Madaket Ditch	2.433	2.433	-	0.061	2.49	0.00%
Long Pond	3.230	1.101	0.975	3.065	5.14	-65.91%
North Head Long Pond	0.238	0.238	0.693	0.995	1.93	0.00%
System Total	**10.605**	**5.570**	**10.805**	**21.49**	**37.86**	**-47.48%**

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

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I. INTRODUCTION

The Madaket Harbor Estuarine System (inclusive of Hither Creek and Long Pond) is located within the Town of Nantucket on the Island of Nantucket, Massachusetts (Figure I-1). The relatively pristine nature of Nantucket's nearshore and Harbor waters (Madaket Harbor and Nantucket Harbor) has historically been a valuable asset to the island. However, concern over the potential degradation of Madaket Harbor water quality began to arise, which resulted in monitoring, scientific investigations and management planning which continues to this day. Madaket Harbor is one of the largest enclosed bays in southeastern Massachusetts and one of the few with a relatively high water quality capable of supporting significant high quality ecological habitats, such as eelgrass beds and shellfish beds. Ironically, it is the pristine nature of this system which may indirectly threaten its ecological health as the coastal waters throughout Southeastern New England become increasingly degraded and the pressure for access and development of remaining high quality environments increases.

The western boundary of the Madaket Harbor system is generally open to Nantucket Sound and Atlantic Ocean waters but somewhat restricted by very dynamic network of sand shoals. Madaket Harbor has a northern shore (Eel Point) bounded by Eel Point Marsh along the Madaket Harbor shore line and sand dunes on the northern side of Eel Point adjacent Nantucket Sound (Figure I-2). The southern boundary of Madaket Harbor is defined by a long sand spit that periodically is breached as was the case in 2007 when a energetic coastal storm breached the spit and created a second opening to Madaket Harbor. That opening has since closed but remained open from 2007 to 2009.

The watershed for this embayment system is distributed entirely within the Town of Nantucket. The potential long-term impacts resulting from the steadily increasing watershed based nutrient inputs, primarily from fertilizers, on-site septic treatment and increased surface runoff associated with increased coastal development has only recently been recognized as a major threat to the health of our coastal waters and that of Madaket Harbor. Because of the potentially long time lags between nutrient related activity within coastal watersheds and the impacts on coastal waters, significant nutrient related water quality degradation can be initiated before the effects become visible. In the case of Madaket Harbor and especially Long Pond, significant in maintaining the water quality within these systems is the flushing rate and tidal exchange with the high quality waters of Nantucket Sound and the Atlantic Ocean.

The morphology, or physical shape of Madaket Harbor and Long Pond is the result of three major processes: glaciation, marine erosion and marine deposition. To a large extent Nantucket owes its existence to the late Wisconsin glaciation. At Nantucket the continental ice sheet reached its maximum southern extent about 21,000 years ago. This event is marked by the terminal Nantucket moraine which stretches from Monomoy southeastward towards Sankaty Head (Figure I-3) and can be identified by the typically hilly, hummocky terrain called the Shimmo Hills. Melt water streams issuing from the glacial front deposited sandy outwash plains to the south and southwest of the moraine and which, combined with the slightly younger outwash deposits across western Nantucket, comprise more than two-thirds of Nantucket's surface (Figure I-4).

Figure I-1. General location of the Madaket Harbor Estuary assessed by the Massachusetts Estuaries Project relative to nutrient related habitat health and nitrogen management planning. The Harbor exchanges tidal waters with Nantucket Sound and the Atlantic Ocean through a network of tidal channels through adjoining sand shoals.

Figure I-2. Major component basins of the Madaket Harbor Estuary system as assessed by the Massachusetts Estuaries Project. Freshwaters enter from the watershed primarily through direct groundwater discharge to Long Pond and Hither Creek as well as to the Harbor proper. Surfacewater from Long Pond also flow to Madaket Harbor via Madaket Ditch and Hither Creek.

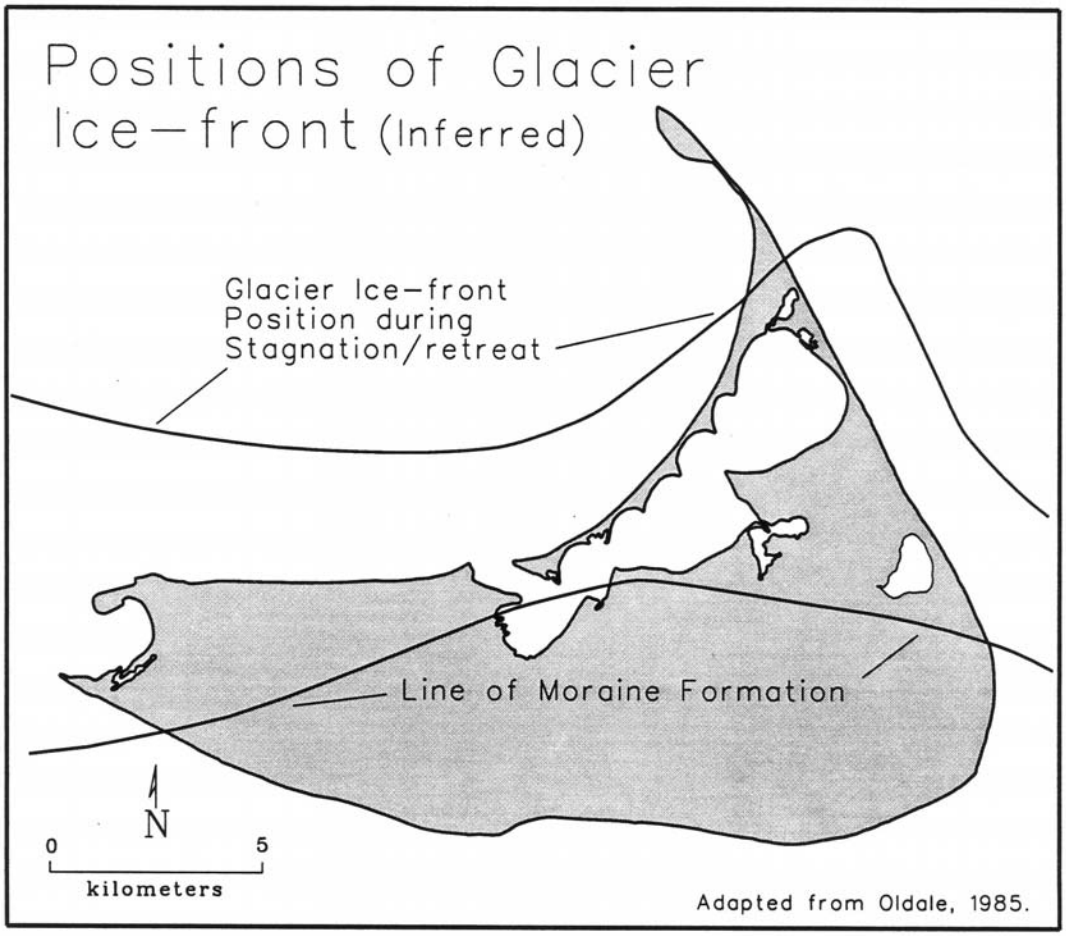

Figure I-3. Simplified map of ice sheet front relative to Nantucket (after Oldale 1985). The southern line indicates a position for the formation of the Nantucket Moraine. A more southerly maximum terminal extension is not shown. The northern stand of the retreating ice sheet was important to the formation of harbor area sediments, moreover there is evidence of glacial lake-bed deposits in Polpis Harbor and a pro-glacial lake in the harbor area.

Within a relatively short period of time after 21,000 yrs B.P., the glacier entered the period of stagnation and retreat. Most of the record of this process has been erased by the erosion of sea level rise and the marine inundation of the Nantucket Sound area, so the following sequence of events is somewhat speculative. The glacial front retreated, first to a line a few kilometers north of the terminal position, and subsequently farther north to Cape Cod (Oldale, 1985). To the north of the moraine in the Shimmo, Quaise, Polpis, Squam Swamp and Quidnet areas in the vicinity of Nantucket Harbor, sediments are a mixture of outwash, ice-contact and glacial lake-bed deposits laid down during the first of these stagnation-retreat events (Figure I-3 and I-4; Oldale, 1985). In the Madaket Harbor area, outwash deposits across the western portion of Nantucket Island also were deposited at this time. Some isolated remnant blocks of ice were buried in sediments during stagnation/retreat and the subsequent melting of these blocks formed depressions called kettles. The location and bathymetry of the North Head of Long Pond suggest it was probably formed this way. Similarly, Long Pond itself may also have been formed as a result of ice influence.

The incorporation of large volumes of water in the continental ice sheets lowered sea level by approximately 300 feet, and the resulting shoreline was on the continental shelf about 75 miles south of the current Nantucket southern shore (Oldale, 1995). Following the contraction of the ice sheets, sea level rose rapidly from about 10,000 to 4,000 yr B.P. and thereafter rose more slowly to reach its present level (Oldale and O'Hara, 1980). With the arrival of the sea at Nantucket the beach processes of erosion and deposition became the major forces shaping the shoreline of Madaket Harbor for the last few thousand years and continues today as evidenced by the constantly shifting sand shoals and the periodic breaching of sand spits.

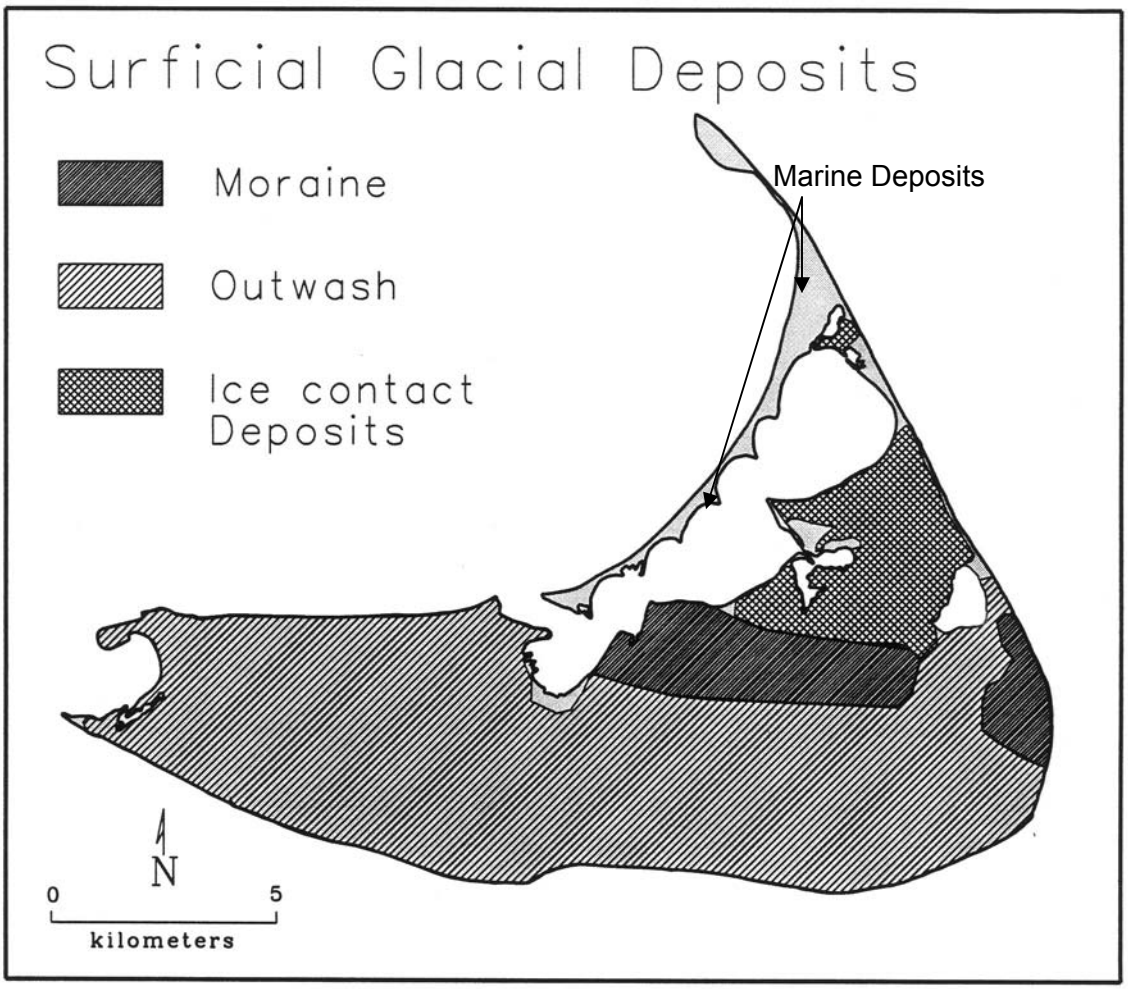

Figure I-4. Generalized distribution of surficial glacial deposits on Nantucket (after Oldale 1985). Extensive deposits of sandy outwash are the result of several depositional events stemming from different ice-front positions. Many of the freshwater and saltwater wetlands in the Polpis Harbor area occur in areas of patchy ice contact (uplands) deposits and fine grained, glacial lake-bed deposits of lower hydraulic conductivity. Coatue and Great Point are marine deposits formed as sea level rose post-glaciation and which are continually being reworked by coastal processes.

The sediments which make-up the fabric of the island are unconsolidated and easily eroded by waves, leading to a continuous change in the island's outline. The sediments range from sorted outwash sands to fine clays to gravels associated with moraine deposits. In

general, the southern shore of Nantucket has been eroded while the northern shore has been an area of marine deposition.

The physical setting of Madaket Harbor and Long Pond is a major control of the harbor ecology and the habitat health of Long Pond. The harbor geometry, adjacent sand shoals and tidal channels, its area, shape and volume control the circulation and residence time of harbor water. Additionally, the relatively restricted circulation of water within Hither Creek as well as the extremely confined nature of Long Pond dramatically affects the habitat health of both these sub-systems to Madaket Harbor. The harbor bathymetry, bottom sediment and seagrass presence/absence affect the distribution of some species by limiting their habitat within the harbor. For example, rooted macrophytes like eelgrass are restricted to a bottom depth to which light penetrates. In addition, the geomorphology and surficial geology of the surrounding upland controls the amount and the pathways of freshwater and nutrient delivery to the Harbor and Hither Creek, both of which are impacted by waters flowing from brackish Long Pond. For example, the highly permeable nature of the watershed soils results in insignificant surface water inflows to Long Pond, with groundwater being the primary discharge pathway. Perhaps the most significant structural parameter supporting the health of Madaket Harbor is the relatively small watershed versus estuarine surface area, the well flushed nature of the Harbor and the moderate level of development in the watershed. The result for the Harbor is that the importance of watershed nitrogen inputs are generally reduced compared to smaller estuaries, like Green Pond (Falmouth) where the watershed is 20 times the estuarine surface. Unfortunately for Hither Creek and Long Pond, as tributary components of the larger Madaket Harbor system, structural features that limit circulation and flushing contribute significantly to the degrading effect nutrient loads have on these sub-systems.

Unlike many of the embayments on Cape Cod and elsewhere in the MEP study region, Madaket Harbor supports relatively healthy aquatic habitats associated with its relatively low nitrogen waters. Eelgrass beds within Madaket Harbor have historically filled most of the seabed throughout the harbor area with the exception of dynamic tidal channels and Hither Creek as can be determined from 1995 and 2001 surveys conducted by MassDEP (MassDEP Eelgrass Mapping Program, Section VII.3) and investigations by the MEP Technical Team. While there has been some evidence of recent gradual declines in coverage, most of the eelgrass beds appear to be stable.

The presence of eelgrass is particularly important to the use of Madaket Harbor as fish and shellfish habitat. The Madaket Harbor System represents an important shellfish resource to the Town of Nantucket, however, shellfishing activities are only conditionally approved throughout the Harbor and prohibited in Hither Creek by the Massachusetts Division of Marine Fisheries as a result of bacterial contamination from watershed run-off and other potential sources and policy closure of the marina area. The DMF has classified Madaket Harbor as a single growing area (NT11) and sub-divided the Madaket Harbor system into subsets whereby the main harbor is considered NT11.3 (conditionally approved), Hither Creek (NT11.1) is classified as prohibited and a small area of the eastern shoreline (NT11.2) is also classified as prohibited, possibly due to the presence of a boat ramp. More offshore waters just outside the western boundary of Madaket Harbor are classified by DMF as approved shellfish growing areas and have been categorized as NT10 to the south, NT12 and NT13 to the west and north of Madaket Harbor (Figure I-5).

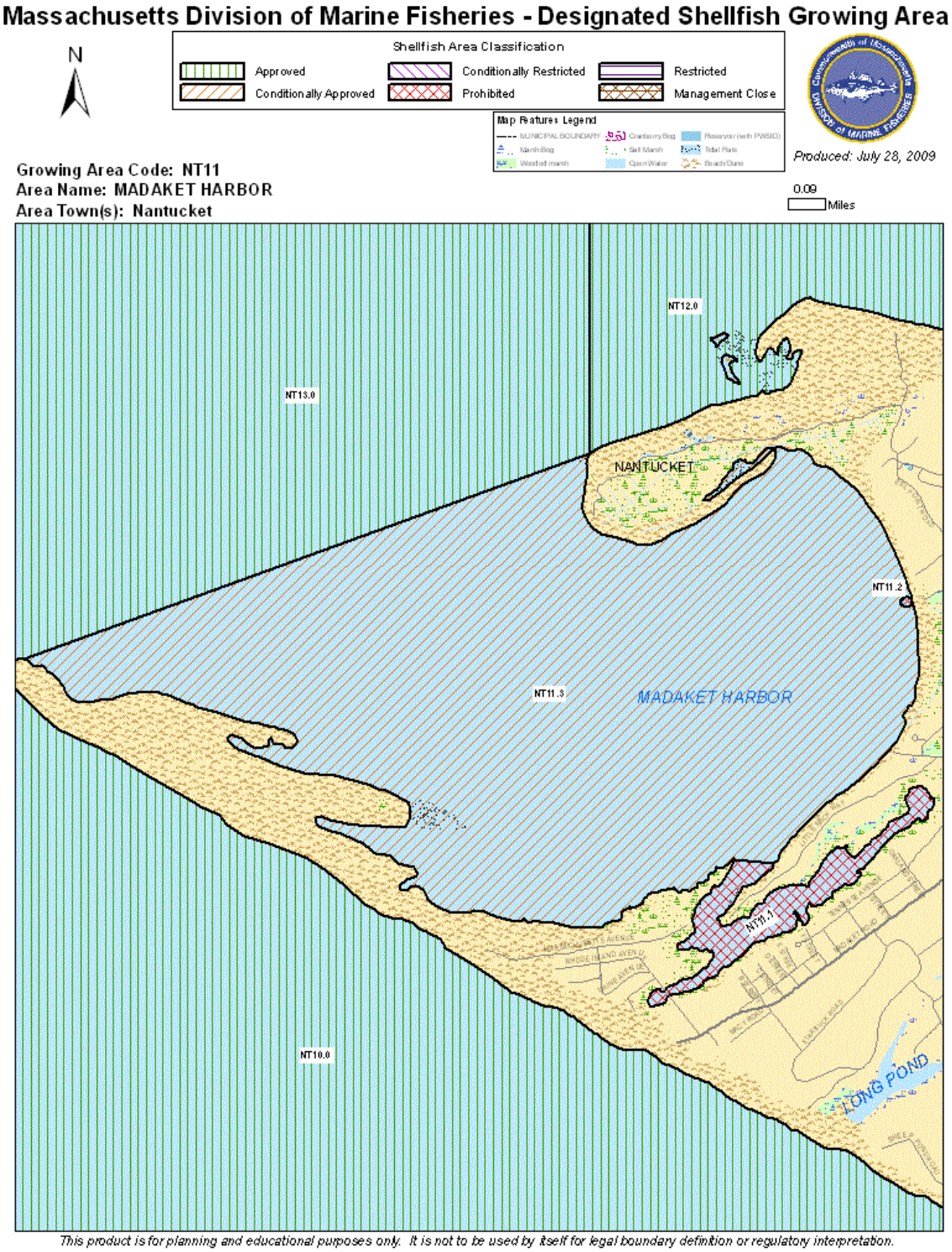

Figure I-5. Massachusetts Division of Marine Fisheries map of designated shellfish growing area NT11 (Madaket Harbor) depicting closed area NT11.1 (Hither Creek).

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, Madaket Harbor, specifically Hither Creek and the North Head of Long Pond and the Long Pond portions of the overall system, as well as all other embayment systems on Cape Cod, are at risk of habitat impairments from increasing nitrogen loads in the groundwater and runoff from the increasingly developed Madaket Harbor watershed.

The primary ecological threat to Madaket Harbor and Long Pond resources is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters has been increasing over the past several decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to Madaket Harbor and other Nantucket embayments (Nantucket Harbor, Sesechacha Pond, Hummock Pond), like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. The Town of Nantucket has been among the fastest growing towns in the Commonwealth over the past two decades, inclusive of areas around Madaket Harbor. While the Town of Nantucket does have a centralized wastewater treatment facility servicing the downtown area, all the residences in the Madaket Harbor and Long Pond Watershed are serviced by septic systems. These unsewered areas contribute significantly to the Madaket Harbor and Long Pond system through transport in direct groundwater discharges to estuarine waters and through surface water flows from Long Pond to Madaket Ditch and Hither Creek.

The Harbor's watershed includes a variety of nutrient sources in addition to residential septic systems, among them groundwater influenced by the nearby landfill, the runoff from roads and application of agricultural and lawn fertilizers, groundwater discharge of runoff from rooftops and natural areas (grasslands, forest, wetland, etc). Atmospheric deposition on the watershed is accounted for in the various land-use evaluations. The greatest level of development and residential load is situated in the nearshore regions of the system. For the current analysis estimates of nitrogen loading to the Harbor from the watershed have been conducted by SMAST scientists and the Cape Cod Commission. Additionally, previous studies for the Town of Nantucket were also incorporated, as appropriate. The bulk of the present watershed nitrogen loading to the Harbor waters is from residential housing and associated sources (roads, driveways, etc.) that exist within the system watershed.

At present, Madaket Harbor and particularly Hither Creek and Long Pond appear to have reached their nitrogen loading thresholds, the level of nitrogen input that a system can tolerate without showing a decline in habitat quality. The clearest evidence of this is the existing low habitat and water quality of Hither Creek (loss of eelgrass) and Long Pond. Additionally, while large portions of Madaket Harbor still supports eelgrass, the slight decline of eelgrass in specific areas would suggest a certain degree of impairment. Consistent with a system at its nitrogen threshold for eelgrass habitat, the bulk of the Harbor is currently supporting healthy benthic animal habitat, critical for supporting the Harbor's and coastal food web (e.g. fish, shellfish, avian fauna, etc).

As the Madaket Harbor and Long Pond watershed has not yet reached build-out (i.e. watershed nitrogen inputs will increase), it appears that nitrogen management will be needed to prevent further declines in system health. However, unlike many embayments in southeastern Massachusetts, nitrogen management associated with Madaket Harbor needs to focus on only modest reductions of present load and controlling future loading. However, unlike Madaket

Harbor, nitrogen management for restoration of the Long Pond system will likely require significant load reductions or an alternative management strategy.

The Town of Nantucket, as the primary stakeholder to the Madaket Harbor embayment system, has been concerned over the quality of this significant coastal resource. The Town has supported a number of studies related to the health of Madaket Harbor and Long Pond and created a revised Nantucket Harbor and Madaket Harbor Action Plan dated May 2009 which is an update to the original Action Plan developed in 1993 and supports management planning for Nantucket and Madaket Harbors. In addition, there has been significant effort related to planning by various groups (e.g. Nantucket Harbor Watershed Work Group, Shellfish Habitat Advisory Board, Nantucket Land Council). The Town of Nantucket's Marine Department and Health Departments have focused on this and other Town embayments for protection and restoration. In addition, the Town of Nantucket has supported a long term Water Quality Monitoring Program which has been collecting data on nitrogen related water quality within the Madaket Harbor and Long Pond System consistently since 2001. The Nantucket Marine Department has collected the principal baseline water quality data necessary for ecological management of the Island's embayments and harbors. The monitoring program is a town-based water quality monitoring program run by the Marine Department (D. Fronzuto and T. Curley and K. Conant, Project Coordination) with technical and analytical assistance from the staff at the Coastal Systems Program at SMAST-UMD and a contract laboratory.

The common focus of the Nantucket Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments of the Island and determine the relationship between observed water quality and habitat health. The Nantucket Water Quality Monitoring Program effort in Madaket Harbor and Long Pond developed a data set that elucidated the long-term water quality of this system. Additionally, as remediation plans for various systems are implemented, the continued monitoring will help satisfy monitoring requirements by State regulatory agencies and provide quantitative information to the Town relative to the efficacy of remediation efforts. The MEP effort builds upon the water quality monitoring program, and previous hydrodynamic and water quality analyses conducted by Applied Coastal Research and Engineering, Applied Science Associates and Earth Tech. The current analysis of the Madaket Harbor and Long Pond system includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Madaket Harbor embayment system, and its major sub-embayment (Hither Creek and Long Pond).

In conjunction with other Town efforts, the Town of Nantucket Planning and Economic Development Commission, as well as the Nantucket Land Council, continue to enhance their tools for gauging future nutrient effects from changing land-uses. The GIS database used in the present MEP evaluation is part of that continuing effort. Based on the wealth of information obtained over the many years of study of the Madaket Harbor and Long Pond System, the Harbor embayment system was included in the early rounds of prioritization of the Massachusetts Estuaries Project to provide state-of-the-art analysis and modeling. This effort was undertaken as a partnership between key Town of Nantucket staff and the MEP Technical Team. Additionally, given that the MEP was able to fully integrate the Towns' on-going data collection and previous ecological assessment efforts undertaken in the harbor, **no additional municipal funds were required** for the conduct of MEP assessment and modeling and nitrogen threshold analysis.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning and nitrogen

management alternatives development needed by the Town of Nantucket. While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for the Town Nantucket to develop and evaluate the most cost effective nitrogen management alternatives to restore the Town's valuable coastal resources currently being impacted by nitrogen overloading. Further, the MEP Linked Watershed-Embayment Model, now calibrated and validated, can be used to evaluate various management approaches for ecological benefit/cost analysis.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

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

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

The Massachusetts Estuaries Project represents the newest generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (MassDEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have

undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts and the Islands.

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region's coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the MassDEP with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

As stated above, the major focus of the MEP is to develop site specific nitrogen thresholds to support nitrogen management planning. The MEP uses a site specific modeling and analysis approach for the assessment of specific estuaries and to evaluate available management options for meeting selected nitrogen goals, protective of embayment health.

The major Massachusetts Estuaries Project goals are to:

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

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

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

The Linked Model has been applied for watershed nitrogen management in ca. 20 embayments throughout Southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach's greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options.

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

Linked Watershed-Embayment Model Overview: The Model provides a quantitative approach for determining an embayment's: (1) nitrogen sensitivity, (2) nitrogen threshold loading levels (TMDL) and (3) response to changes in loading rate. The approach is fully field validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-6). This methodology integrates a variety of field data and models, specifically:

- Monitoring - multi-year embayment nutrient sampling
- Hydrodynamics -
  - embayment bathymetry
  - site specific tidal record
  - current records (in complex systems only)
  - hydrodynamic model
- Watershed Nitrogen Loading
  - watershed delineation
  - stream flow (Q) and nitrogen load
  - land-use analysis (GIS)
  - watershed N model
- Embayment TMDL - Synthesis
  - linked Watershed-Embayment N Model
  - salinity surveys (for linked model validation)
  - rate of N recycling within embayment
  - D.O record
  - Macrophyte survey
  - Infaunal survey

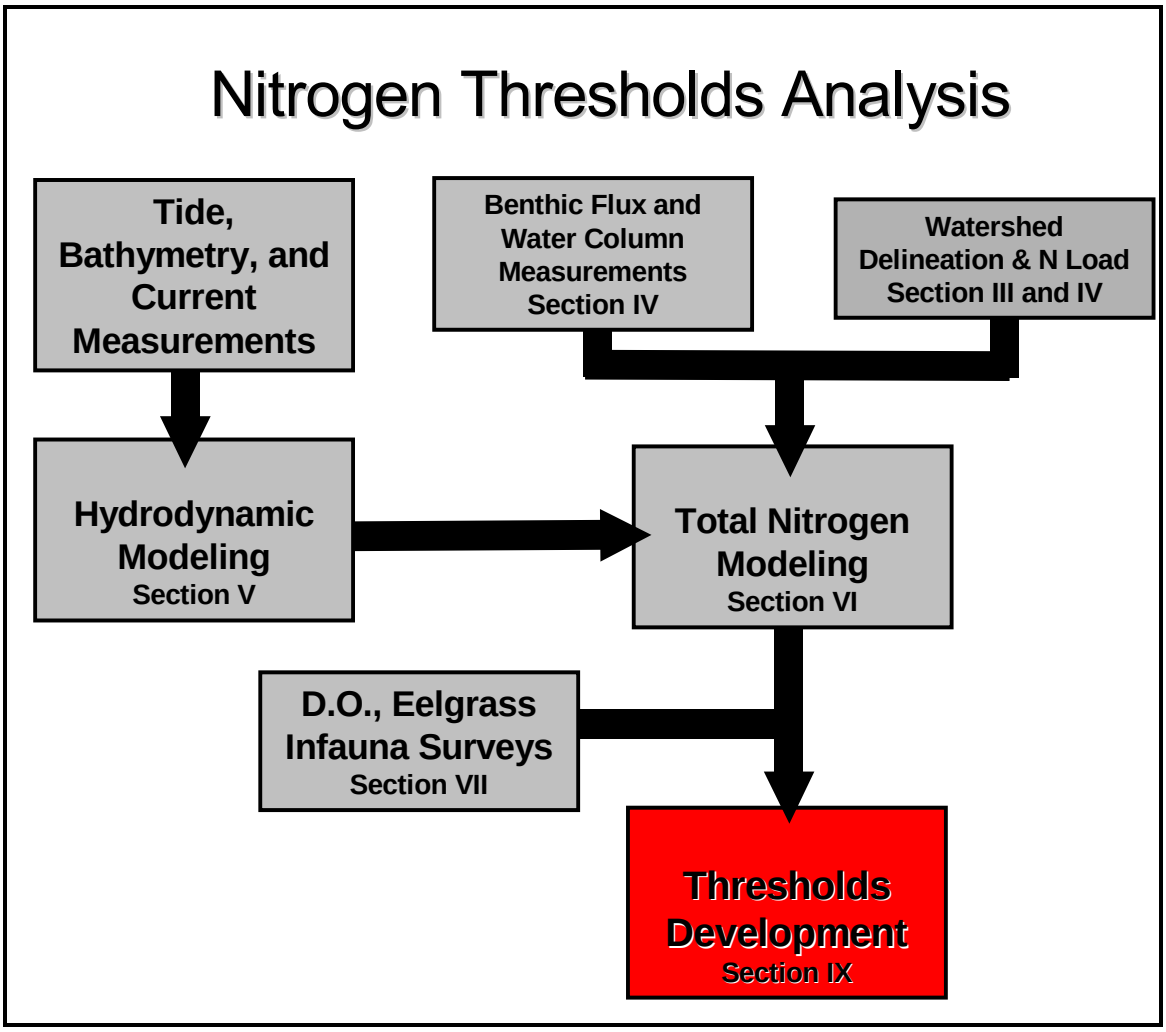

Figure I-6. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

I.2 NITROGEN LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In sandy glacial outwash aquifers, such as in the watershed to the Nantucket Harbor embayment system, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer mineral (Weiskel and Howes 1992). Since even Cape Cod, Nantucket and Martha's Vineyard "rivers" are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems on Cape Cod (DeSimone and Howes 1998, Weiskel and Howes 1992, Smith *et al.* 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). Tidal reaches within the Nantucket Harbor system 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 and nutrient related water quality degradation occurs. As nearshore coastal salt ponds and embayments are the primary recipients of nutrients carried via surface and groundwater transport from terrestrial sources, it is clear that activities within the watershed, often miles from the water body itself, can have chronic and long lasting impacts on these fragile coastal environments.

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

Fortunately, within the Madaket Harbor Estuarine system (as opposed to Hither Creek and Long Pond), large portions of the system appear to be below the nutrient threshold and therefore are supportive of healthy aquatic habitat. By contrast, the Hither Creek and Long Pond components of the overall system, sub-basins to Madaket Harbor, appear to be well beyond their respective abilities to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated in these areas of the system and eelgrass beds have been lost from Hither Creek. The result is that nitrogen management of this system is aimed at limited restoration and limitation of new nitrogen sources rather than maintenance of existing conditions, particularly for Hither Creek and Long Pond.

In general, nutrient over-fertilization is termed “eutrophication” and when the nutrient loading is primarily from human activities, it is considered “cultural eutrophication”. Although the influence of human-induced changes has increased nitrogen loading to the system and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within a given embayment system could potentially occur without human influence and must be considered in the nutrient threshold analysis. While this finding would not change the need for

restoration, it would change the approach and potential targets for management. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a "pristine" system.

I.3 WATER QUALITY MODELING

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

The MEP water quality evaluation examined the potential impacts of nitrogen loading into the Madaket Harbor and each of its sub-basins: Hither Creek and the associated Long Pond and North Head of Long Pond components. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations performed previously by the USGS, the Town of Nantucket, Horsely & Witten Inc. and the Earth Tech Study of the Madaket Harbor watershed. The watershed reflects the delineation in the Town of Nantucket Madaket Harbor Watershed Protection District.

Virtually all nitrogen entering the Madaket Harbor and Long Pond embayment system is transported by freshwater, predominantly groundwater discharging directly to the system, or through atmospheric deposition directly to the estuary surface. Concentrations of total nitrogen and salinity of Nantucket Sound source waters and throughout the Madaket Harbor / Long Pond system was taken from the Town of Nantucket Water Quality Monitoring Program (associated with the Coastal Systems Program at SMAST) and from previous sampling of Nantucket Sound nearshore waters and the Harbor by MEP staff. Measurements of nitrogen and salinity distributions throughout estuarine waters of the system were used to calibrate and validate the water quality model (under existing loading conditions).

I.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project Linked Watershed-Embayment Management Modeling Approach to the Madaket Harbor Estuarine System (inclusive of Hither Creek, Long Pond and the North Head of

Long Pond) for the Town of Nantucket. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission, Town of Nantucket Assessors, Nantucket Planning & Economic Development Commission and Nantucket Land Council data. Offshore water column nitrogen values were derived from an analysis of monitoring stations in Nantucket Sound (Section IV).

Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Section VI. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of each embayment was performed that included a review of existing water quality information, temporal changes in eelgrass distribution, dissolved oxygen records and the results of a benthic infaunal animal analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration in a given estuarine basin and to determine the sensitivity of the habitats within the Harbor to additional nitrogen loading (e.g. buildout). The nitrogen reduction scenario used by the MEP represents only one of many solutions and is produced to assist the Town in developing a variety of alternative nitrogen management options for the Nantucket Harbor System. Finally, analysis of the Madaket Harbor and Long Pond System was undertaken relative to an alternative loading scenario involving removal of nitrogen load from the landfill. The result of the nitrogen modeling for this alternative loading scenario is presented in Section IX.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

In most marine and estuarine systems, such as the Madaket Harbor / Long Pond System, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. This approach has been formalized through the development of tools for predicting nitrogen loads from watersheds and the concentrations of water column nitrogen that may result. Additional development of the approach generated specific guidelines as to what is to be considered acceptable water column nitrogen concentrations to achieve desired water quality goals (e.g., see Cape Cod Commission 1991, 1998; Howes et al. 2002).

These tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. The present Massachusetts Estuaries Project (MEP) study focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Madaket Harbor / Long Pond System. As the MEP approach requires substantial amounts of site specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of “data mining” and to gather additional information on an estuary’s habitat quality or unique features.

A number of studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Madaket Harbor System over the past two decades.

Madaket Harbor / Long Pond Annual Report (2005, 2006 and 2007) – These reports were prepared by Keith Conant, past Town Biologist working for the Nantucket Marine Department. The reports were developed as a summary of water quality monitoring undertaken in the summers of 2005, 2006 and 2007. Each annual report gives a basic description of the systems nutrient characteristics and observations of changes. Some of the conclusions from the 2005 and 2006 annual report indicate that the harbor remains in good/fair condition, primarily

because of its shape and rapid flushing time. Nevertheless, the harbor is closed to shell fishing for half the year. Conant concluded that this is in large part due to the water quality in Hither Creek, and Long Pond; which was stated to be the most severely degraded water bodies on the island of Nantucket.

While the conclusions of the Annual Report for 2007 are not noticeably different than for 2006, the report does document the day when the breach opened up through Smith's Point as a result of a strong Nor'easter. On April 15th 2007, the storm breached Smith's Pt., recreating Esther's Island at approximately the same location as where it previously existed. Based on observations, initially the opening was 50 to 60 yards wide, and an average depth of 15 feet reported by local fishermen. A great deal of erosion occurred at the new Smith's Pt., and the west end of the island in 2007. The breach stayed open to Madaket Harbor, changing currents, and filling in harbor flats with deposited sands from long shore drift. In 2007 the breach remained open, 60 to 70 yards wide, with an unknown depth. Subsequently, a large spit formed on the inside of the harbor running roughly west to northeast in a crescent shape off Esther's. Based on observations by the Marine Department, exposed at low tide, the spit was approximately 500 yards long, and 20 yards wide and at the time buried large areas of adjacent eel grass beds. Since the report was written, the breach closed returning circulation patterns to what existed at the time of the MEP data collection. The breach remained open for approximately 2.5 years, slowly becoming more constricted until closing in November 2009.

Nantucket and Madaket Harbors Action Plan (2009) - The 2009 Nantucket and Madaket Harbors Action Plan carries forward a number of recommendations from the 1993 Harbors Action Plan that remain important and identifies new recommendations that have arisen in the intervening years. The Plan focuses on the improvement of public access, maintaining and improving appropriate water-dependent uses within the harbors, and protection of natural resources and water quality as it relates to commercial and recreational shellfishing. The Plan includes a comprehensive inventory and analysis of harbor resources and uses, and identifies specific goals, objectives and recommendations for the three above mentioned focus areas.

Despite the designation of highest quality water for Madaket Harbor (SA), the 2009 update of the Harbors Action Plan still stresses there are water quality concerns. Both the 1993 and the 2009 Nantucket and Madaket Harbors Action Plans identified three potential pollution problems: pathogen contamination, excessive nutrient enrichment, and toxic contamination. While the 1993 Action Plan did not explicitly state that nutrient enrichment was a "current problem", the 1993 Action Plan did note that the island's 1993 residential population was forecasted to increase. The resulting increase in development and associated increases in fertilizer and septic leachate was presented as a potential cause of future nutrient enrichment. Of note, the 2009 update to the 1993 Action Plan is much more cognizant of the threat that nutrient enrichment and decreased water quality poses to the Town of Nantucket. As such the 2009 Action Plan presents a clear water quality goal with associated sets of objectives and recommendations aimed at water quality management which are consistent with the objectives of the Massachusetts Estuaries Project.

Madaket Harbor Comprehensive Wastewater Master Plan (Earth Tech, 2001-2005). - This report was prepared by Earth Tech for the Nantucket Department of Public Works to guide management of wastewater across the Island of Nantucket and specifically Madaket Harbor. The Master Plan was developed in multiple phases as follows:

Earth Tech, Inc. 2001. Comprehensive Wastewater Management Plan and Environmental Impact Report, Phase I – Needs Analysis and Screening of Alternatives. Prepared for the Nantucket Department of Public Works.

Earth Tech, Inc. 2003. Comprehensive Wastewater Management Plan and Draft Environmental Impact Report Phase II – Alternatives and Site Identification. Prepared for the Nantucket Department of Public Works

Earth Tech, Inc. 2004. Phase III – Comprehensive Wastewater Management Plan and Final Environmental Impact Report. Prepared for the Nantucket Department of Public Works.

Earth Tech, Inc. 2005. Drainage Outfall Evaluation: Nantucket, Massachusetts. Prepared for the Nantucket Department of Public Works.

Madaket Harbor Circulation Study (ASA 2002) – In response to bacterial contamination and nutrient loading concerns in Madaket Harbor, Applied Science Associates (ASA, Inc.) was contracted by the Massachusetts Department of Environmental Protection to conduct a survey of water quality characteristics in Madaket Harbor, inclusive of Long Pond, and develop a hydrodynamic and flushing model. This effort was completed as part of the Massachusetts Watershed Initiative. A field program was undertaken in order to collect hydrodynamic and water quality data needed to parameterize and calibrate a numerical model as well as provide an initial assessment of the health of the system. ASA, Inc. utilized a proprietary numerical model (Hydromap-BP) to simulate circulation in Madaket Harbor and Long Pond. The model was calibrated based on tidal stages and for Long Pond, calibration focused on amplitude and phase relationships of the dominant diurnal tidal frequency which they determined to be K1. The hydrodynamic model calibration/validation procedure did not include any current measurements to ascertain velocities or volumetric exchange at critical junctures in the overall system. A numerical mass transport model was used to simulate dye dilution rates to ultimately estimate flushing times from five specific regions of the overall system. Since a comprehensive dye study was outside the scope of the ASA modeling effort, ASA, Inc. used a USEPA recommended value for dispersion (1.0 m^2/s) acknowledging that this approach provided merely an estimate of flushing times in the system and that a comprehensive dye study should be undertaken to more accurately determine dispersion.

Based on the water quality data collected and results of the hydrodynamic modeling, ASA concluded that both Long Pond and Hither Creek were eutrophic and that habitat quality in Madaket Harbor was relatively high. Additionally, the numerical model estimated that Madaket Harbor and Hither Creek flushed within 5 and 3 days respectively. Madaket Ditch flushed within 0.25 days (less than one tidal cycle), the North Head of Long Pond flushed after 76 days and the southern portion of Long Pond had a flushing time of approximately 183 days. The field data collection effort also revealed that all the surface water sites sampled had fecal coliform present and given the number of potential sites where contamination could originate, that a sanitary survey of the entire system was warranted.

Town of Nantucket Water Quality Monitoring Program (2001-2007) – Over the past decade nutrient sampling of Madaket Harbor and Long Pond has been undertaken at a variety of stations (Figure II-1) throughout the system by a variety of parties including the Town of Nantucket Marine Department, Northeast Aquatic Research (under contract to the Marine Department) and the Coastal Systems Program-SMAST. Sampling of Madaket Harbor got started at an initial five stations (M1-M5) as early as 1989 and 1990 when members of the MEP Technical Team were at the Woods Hole Oceanographic Institution. There was no nutrient

related water quality monitoring from 1991-2001. In 2001 monitoring was resumed by staff from Northeast Aquatic Research, CT (stations MHD, SHD, HC, LPS, LPC and LPN). Starting in 2002, the Nantucket Marine Department partnered with SMAST-Coastal Systems Program scientists to unify the sampling protocols in order to build the baseline water quality monitoring record needed for the execution of the MEP analysis on the Madaket Harbor / Long Pond estuarine system. The Nantucket Marine Department working with SMAST staff coordinated and executed the water quality surveys of the Madaket Harbor / Long Pond system, beginning in 2002 and for stations M1-M10. In 2003 and 2004 stations in Long Pond were added to augment the previously initiated water quality sampling effort in that pond. With three years of consistently collected base data in hand, sampling at a reduced number of stations was continued in the summer of 2005 by the Nantucket Marine Department. Sampling was continued in 2006 and 2007 after which time sampling ceased due to funding constraints. Given the different analytical approaches used for assays over the course of the program, the data was screened based upon MEP protocols. Virtually all of the monitoring data met requirements, except for total nitrogen analysis by Keljdal digestion, which yield slightly high results. After review, data were used to form the needed baseline for implementation of the MEP assessment and threshold development.

Recently, sampling has been resumed for the summer of 2010 with the Marine Department working collaboratively with SMAST-Coastal Systems Program to continue the baseline relative to the coming MassDEP/USEPA TMDL for these aquatic systems. For Madaket Harbor and Long Pond as well as the other estuarine systems of Nantucket, the focus of the effort has been to gather site-specific data on the current nitrogen related water quality throughout the estuarine reach of the system to support assessments of habitat health. These baseline water quality data are a prerequisite to entry into the MEP and the conduct of its Linked Watershed-Embayment Approach. Throughout the water quality monitoring period, sampling was undertaken between 4 and 6 times per summer between the months of June and September. The Town based Water Quality Monitoring Program for Madaket Harbor/Long Pond developed the baseline data from sampling stations distributed throughout the Harbor as well as the main tidal channel of Hither Creek and the tributary brackish water sub-system of Long Pond and North Head of Long Pond (Figure II-1). As remediation plans for this and other various systems on Nantucket are implemented, monitoring will be needed to provide quantitative information to the Town as to changing conditions and the efficacy of remediation efforts.

Implementation of the MEP's Linked Watershed-Embayment Approach incorporates the quantitative water column nitrogen data (2001-2005), with the 3 primary years being 2002, 2003, 2004, gathered by the Nantucket Water Quality Monitoring Program and watershed and embayment data collected by MEP staff. The MEP effort also builds upon previous watershed delineation and land-use analyses as well as historical eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Madaket Harbor / Long Pond Estuarine System. The MEP has incorporated data from appropriate previous studies to enhance the determination of nitrogen thresholds for the Madaket Harbor/Long Pond System and to reduce costs of restoration for the Town of Nantucket.

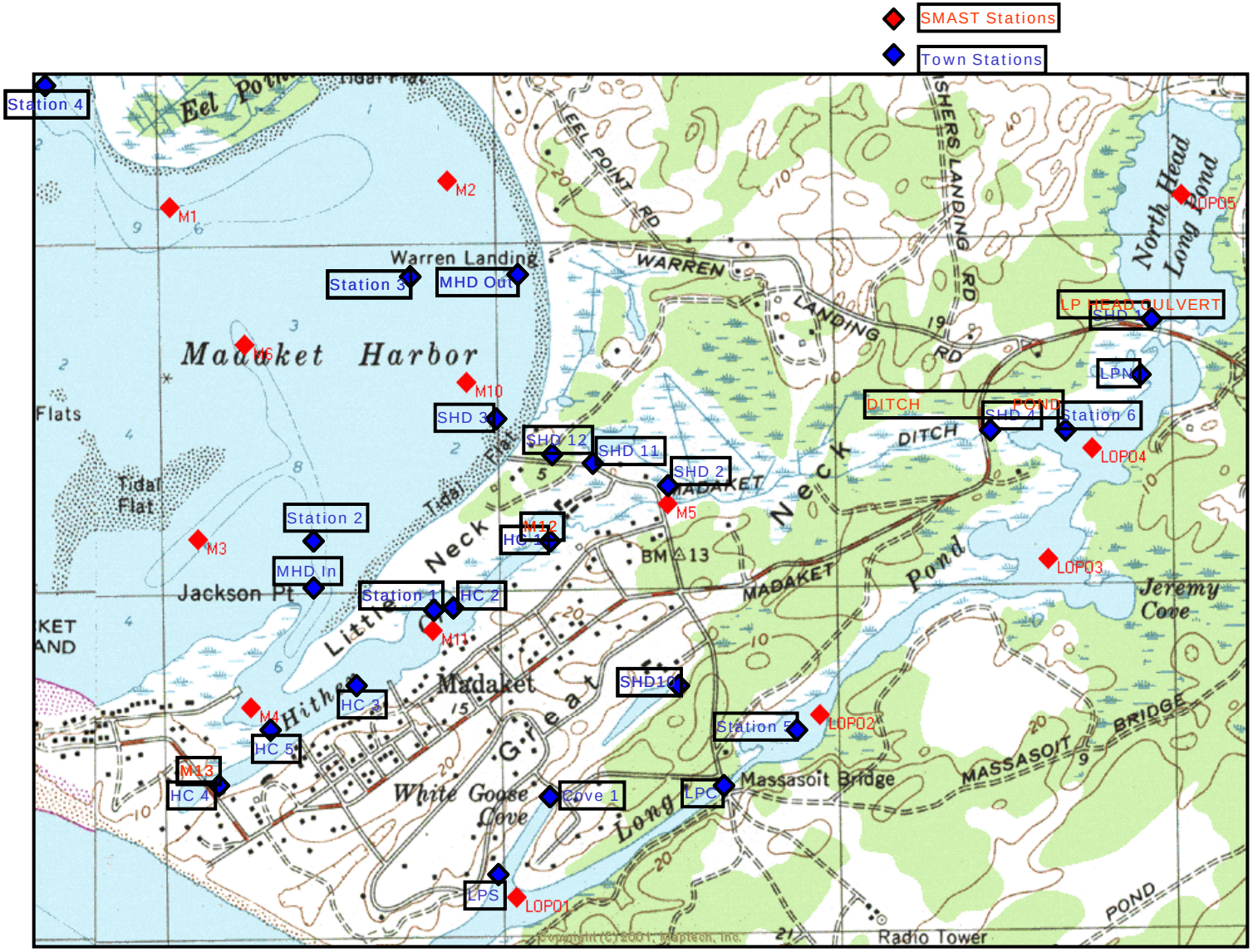

Figure II-1. Town of Nantucket Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the Nantucket Marine Department/SMAST staff.

Regulatory Assessments of Madaket Harbor / Long Pond Resources - The Madaket Harbor / Long Pond Estuary contains a variety of natural resources of value to the citizens of Nantucket 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 Madaket Harbor / Long Pond Estuary these include:

- Mouth of River designation - MassDEP (Figure II-2)
- Designated Shellfish Growing Area – MassDMF (Figure II-3)
- Shellfish Suitability Areas - MassDMF (Figure II-4)
- Anadromous Fish Runs - MassDMF (Figure II-5a and II-5b)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-6a and II-6b)

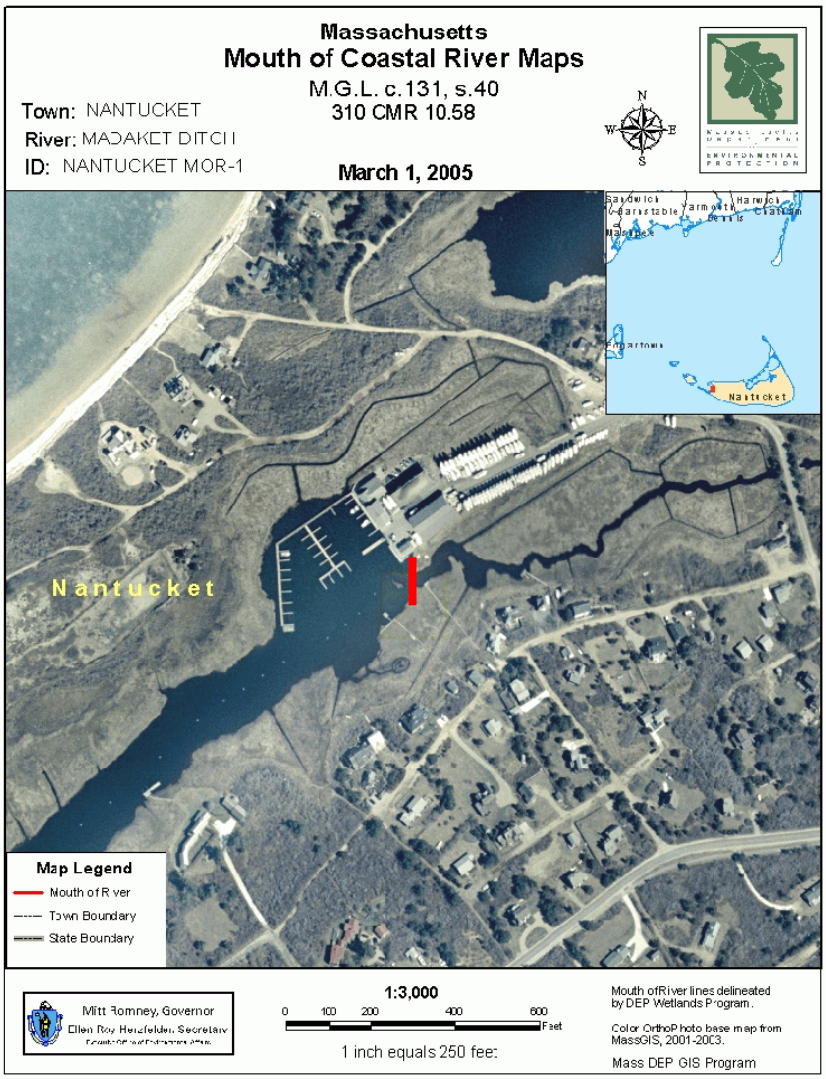

Figure II-2. Regulatory designation for the mouth of "River" line under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

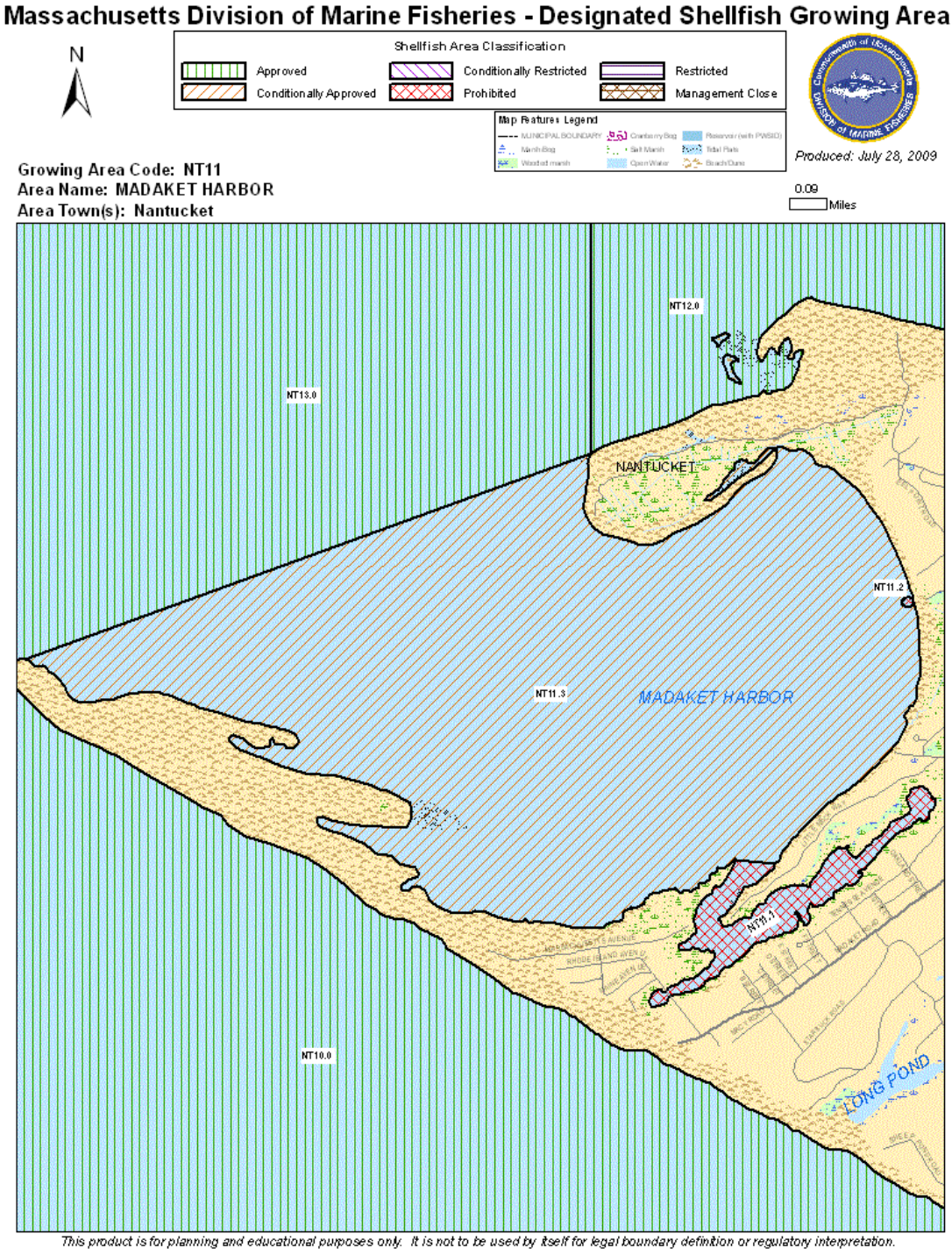

Figure II-3. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

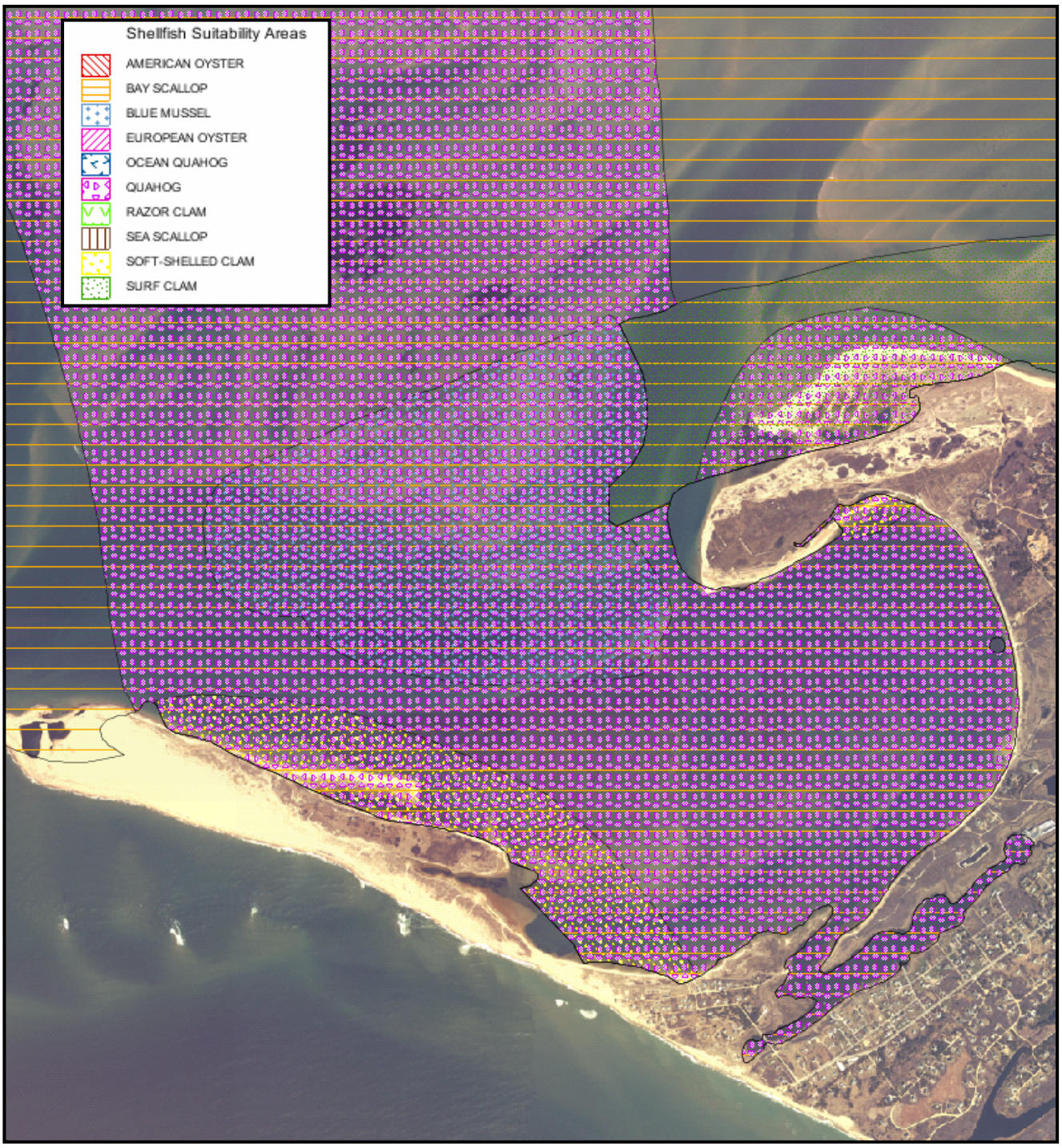

Figure II-4. Location of shellfish suitability areas within the Madaket Harbor Estuary (inclusive of Hither Creek) as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence". Note that there are no shellfish suitability areas within Long Pond.

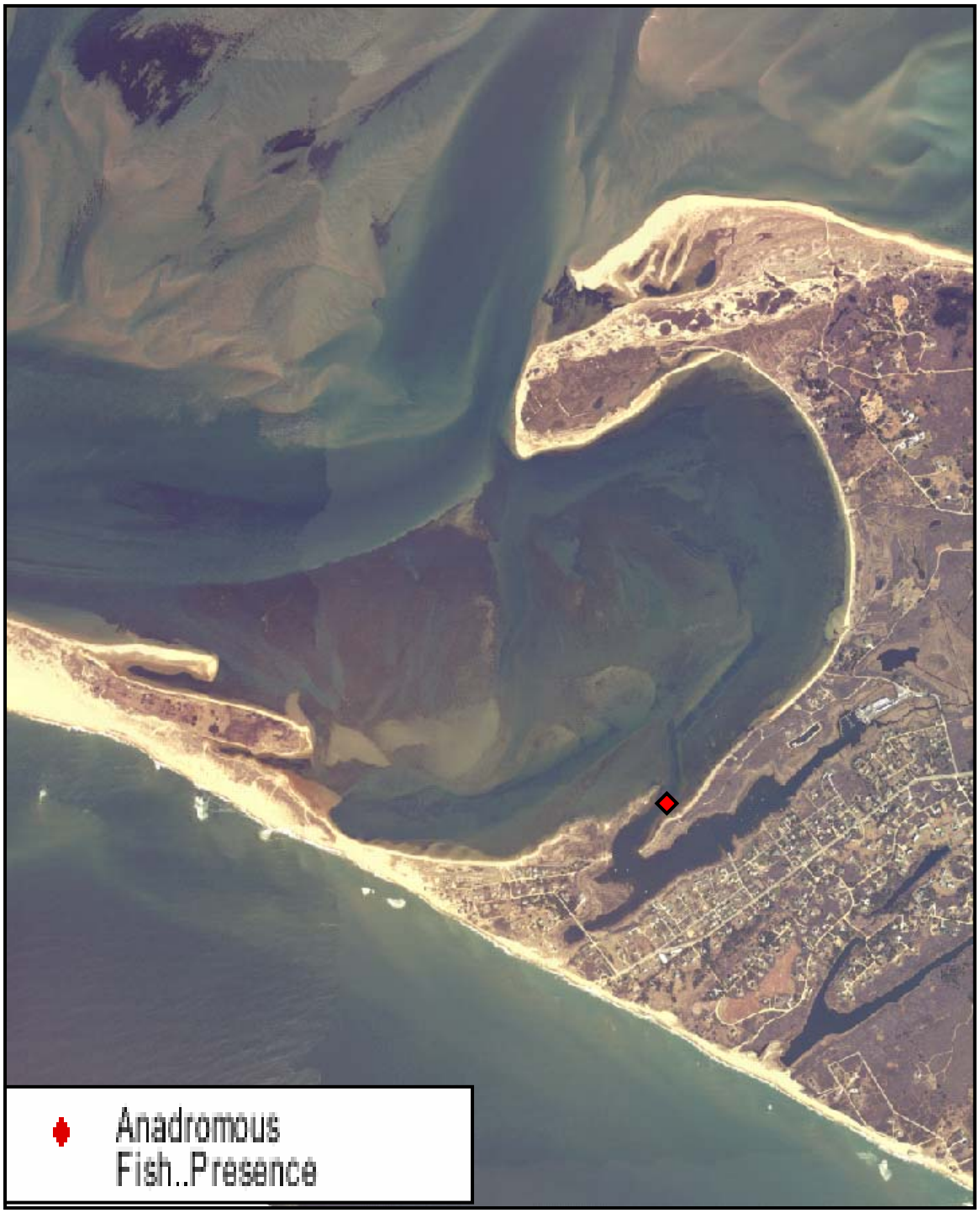

Figure II-5a Anadromous fish runs within the Madaket Harbor portion of the Madaket Harbor/Long Pond estuarine system as determined by Mass Division of Marine Fisheries. The red diamonds show areas where fish were observed.

Figure II-5b. Anadromous fish runs within the Long Pond portion of the Madaket Harbor/Long Pond estuarine system 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 Madaket Harbor portion of the Madaket Harbor/Long Pond estuarine system as determined by - NHESP.

Figure II-6b. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Long Pond portion of the Madaket Harbor/Long Pond estuarine system as determined by - NHESP.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

Nantucket Island is located near the southern edge of late Wisconsinan glaciation (Oldale and Barlow, 1986). As such, the geology of the island is largely composed of outwash plain and moraine with reworking of these deposits by the ocean that has occurred since the retreat of the glaciers. The moraine, which is located relatively close to Nantucket Harbor, consists of unsorted sand, clay, silt, and gravel, while the outwash plain, which tends to be located toward the southern half of the main portion of the island is composed of stratified sands and gravel deposited by glacial meltwater. The groundwater system of Nantucket Island is generally characterized by a shallow, unconfined aquifer and a separate deep, confined aquifer, although some recent deep well drillings have suggested that there are additional confining units of undetermined extent that are interlaced in the unconfined layer (Lurbano, 2001). These characterizations of the geology, including the installation of numerous long-term monitoring wells by the US Geological Survey over the last few decades, have provided the basis for subsequent activities, including the delineation of estuary watersheds. The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS) to assist in the delineation of estuary watersheds.

During the development of the Nantucket Water Resources Management Plan, an island-wide groundwater mapping project, many of the USGS water level monitoring wells were utilized to complete a detailed characterization of the configuration of the water table across Nantucket Island (HWH, 1990). Estuary watershed delineations completed in areas with relatively transmissive sand and gravel deposits, like most of Cape Cod and the Islands, have shown that 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). This approach was used by HWH to complete a watershed delineation for Madaket Harbor (Figure III-1); this watershed delineation has been largely confirmed by subsequent water table characterizations (*e.g.*, Lurbano, 2001, Gardner and Vogel, 2005). The watershed to Madaket Harbor has been adopted in the town zoning bylaws as the Madaket Harbor Watershed Protection District.
(http://www.nantucket-ma.gov/Pages/NantucketMA_IT/gismapsfolder/madaketharborwpd.pdf).

III.2 MADAKET HARBOR CONTRIBUTORY AREAS

MEP staff compared the Town-approved Madaket Harbor watershed to a 2007 aerial base map and corrected differences in the outer watershed boundary based on some coastal shoreline changes. In addition, MEP staff developed internal subwatersheds based on the location of surface water gaging sites (see Chapter IV.2) and major wetland systems. These subwatershed delineations to North Head/Long Pond, Madaket Ditch, and Hither Creek were completed based on this information and best professional judgment, including watershed/water table characterization experience in similar geologic settings. Recharge within these areas was also compared to estimate freshwater flows derived from salinity data at two critical gaging locations. In addition, watershed recharge volumes were compared to the overall salinity regime measured in water quality samples throughout the estuary (see Chapter VI). Overall, there are six (6) subwatersheds delineated within the Madaket Harbor system watershed and the MEP stream gaging effort corroborated the watershed delineations used in the MEP analysis of Madaket Harbor and Long Pond.

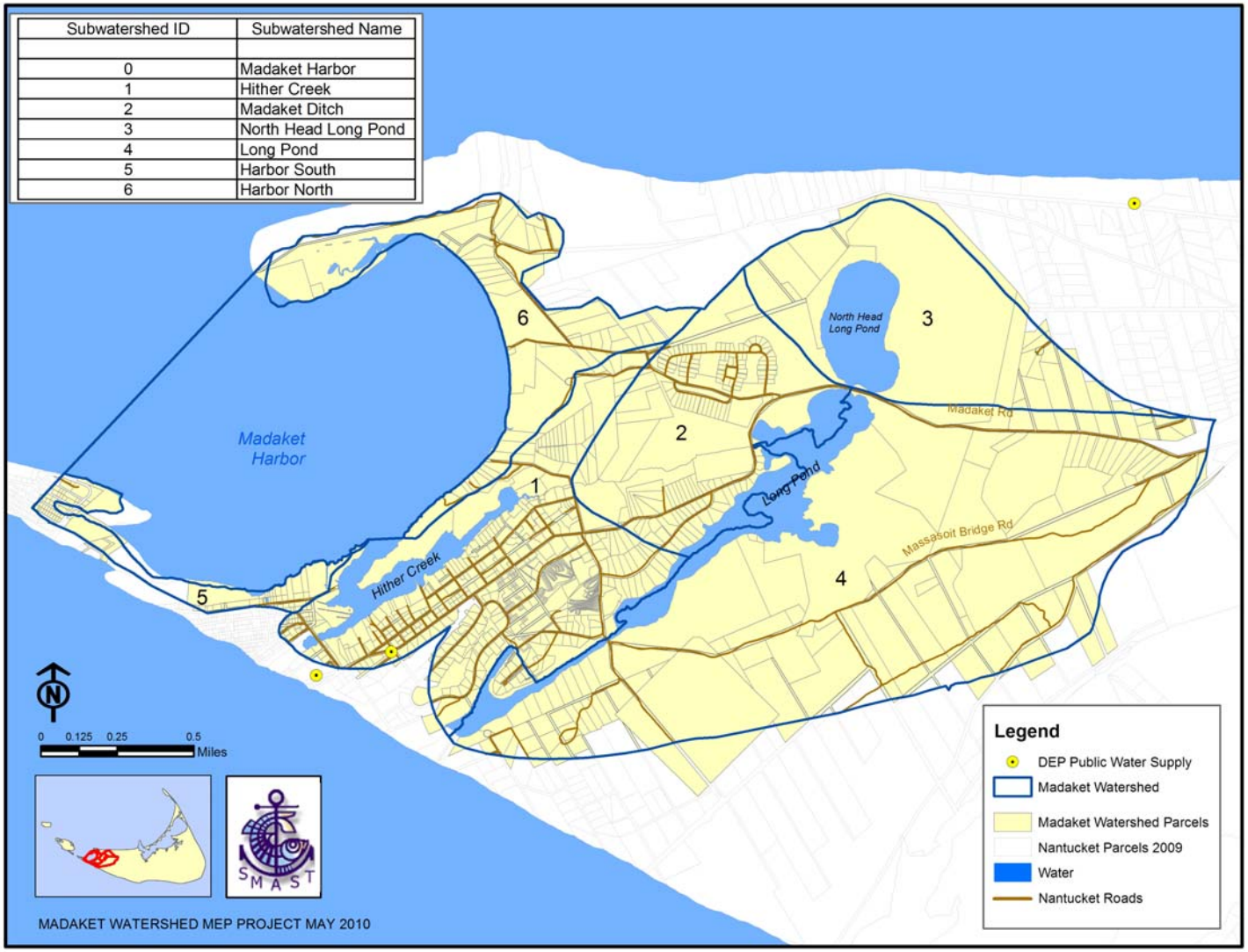

Figure III-1. Watershed and sub-watershed delineations for the Madaket Harbor estuary system. Sub-watersheds were delineated based on functional estuarine sub-units in the water quality model (see section VI), flow gaging locations, wetland delineations, and best professional judgment. Outer watershed boundary is based on HWH (1990) and Town of Nantucket Watershed Protection District.

Table III-1 provides the daily discharge volumes for various sub-watersheds as calculated from the watershed areas and a recharge rate of 27.25 inches per year; these volumes were used to assist in the salinity calibration of the tidal hydrodynamic models. The recharge rate is larger than the 18 inches per year estimated by HWH. HWH (1990) developed their recharge rate base on previous US Geological Survey estimates (e.g., Knott and Olimpio, 1986). Subsequent USGS groundwater modeling on Cape Cod has shown that higher recharge rates are necessary to balance water table elevations in the most recent regional groundwater models (Walter and Whealan, 2005, Masterson, 2004). Given that Nantucket was formed during the same glacial period as Cape Cod and is subject to largely the same weather patterns, it is reasonable to assume that the hydrogeology and recharge rates are similar. This recharge rate is also consistent with the upper portion of a range of calculated recharge on Nantucket based on tritium measurements (Knott and Olimpio, 1986). The overall estimated groundwater flow into Madaket Harbor from the MEP delineated watershed is 16,081 m3/d.

Table III-1. Daily groundwater discharge from each of the sub-watersheds to the Madaket Harbor Estuary.

Watershed	Watershed #	Discharge	
		m^3/day	ft^3/day
Hither Creek	1	2,722	96,118
Madaket Ditch	2	2,263	79,913
North Head Long Pond	3	2,000	70,644
Long Pond	4	7,028	248,191
Madaket Harbor South	5	449	15,853
Madaket Harbor North	6	1,619	57,174
TOTAL		16,081	567,892

NOTE: Discharge rates are based on 27.25 inches per year of recharge (Walter and Whealan, 2005).

It should be noted that the western boundary of the Long Pond subwatershed (#4) is based on a review of the area of open water on current aerial maps of Long Pond (e.g. Google Earth). The parcel area of the open water of Long Pond, which is shaded blue in Figure III-1, includes low lying areas and bordering wetlands. The inconsistency between the parcel coverage and actual open water is among the issues that the Town and County are working to reconcile (personal communication, Leslie Snell and Andrew Vorce, Planning Department, March 11, 2010). For the purposes of the MEP assessment, staff utilized the area of open water based on review of aerial maps.

Review of watershed delineations for Madaket Harbor allows new hydrologic data to be reviewed and the watershed delineation to be reassessed. The evaluation of older data and incorporation of new data during the development of the MEP watershed model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model used for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon the land-uses that are included/excluded within the contributing areas. Small errors in watershed area can result in large errors in loading if a large source is counted in or out. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the downgradient 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 Madaket Harbor system (Section V.1).

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

Management of nutrient related water quality and habitat health in coastal waters requires determination of the amount of nitrogen transported by freshwaters (surface water flow, groundwater flow) from the surrounding watershed to the receiving embayment of interest. In southeastern Massachusetts, the nutrient of management concern for estuarine systems is nitrogen and this is true for the Madaket Harbor / Long Pond 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. This latter natural attenuation process results from biological processes that naturally occur within 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. Burial of nitrogen is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source of nitrogen to embayment waters or in some cases a sink for nitrogen reaching the bottom. Failure to include the nitrogen balance of estuarine sediments generally leads to errors in predicting water quality, particularly in determination of summertime nitrogen load to embayment waters.

The MEP Technical Team staff developed nitrogen-loading rates (Section IV.1) to the Madaket Harbor embayment system and watershed (Section III). The Madaket Harbor watershed was sub-divided to define contributing areas to each of the major sub-embayments inclusive of Long Pond. A total of six (6) sub-watersheds were delineated for the Madaket Harbor Estuarine System. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to each portion of the embayment (see Chapter III).

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other detailed studies is applied to other portions. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon subwatershed-specific land uses and pre-determined nitrogen loading rates. For the Madaket Harbor embayment system, the model used Town of Nantucket land-use data transformed to nitrogen loads using both regional nitrogen loading factors and local watershed-specific data (such as average town water use and parcel-specific water use). Determination of the nitrogen loads required obtaining watershed-specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the “potential” or unattenuated nitrogen load to each receiving embayment,

since attenuation during transport has not yet been included. Stream flow and associated surface water attenuation based on collected water quality data in Madaket Harbor and Long Pond is included in the MEP nitrogen attenuation and freshwater flow investigation, presented in Section IV.2.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. However, the watershed to Madaket Harbor contains only smaller aquatic features that do not have separate watersheds delineated and, thus they are not explicitly included in the watershed analysis. If these small features were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (<10%) overestimated given the distribution of nitrogen sources and these features within the watershed. Based upon these considerations, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the six sub-watersheds that directly discharge groundwater to the estuary. Internal nitrogen recycling was also determined throughout the tidal reaches of the Madaket Harbor Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Estuaries Project staff obtained digital parcel and tax assessor's data from the Town and County of Nantucket Geographic Information Systems Department (Nathan Porter, GIS Coordinator, January 2010). Digital parcels and land use/assessors data are from 2009. These land use databases contain traditional information regarding land use classifications (MADOR, 2008) plus additional information developed by the town and county. Zoning information is also included in the town and county data, including zoning changes in the Madaket Harbor watershed that were approved at the 2009 Special Town Meeting (Leslie Snell, Senior Planner, February 2010).

Figure IV-1 shows the land uses within the Madaket Harbor Estuary watershed area. Land uses in the study area are grouped into six land use categories: 1) residential, 2) commercial, 3) undeveloped (including residential open space), 4) public service/government, including road rights-of-way, 5) marsh/sandbars, and 6) unclassified (e.g. parcels that do not have complete information in the town assessor's database). These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2008). "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (e.g., wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges.

As noted in Chapter III, the watershed to Long Pond excludes some areas that are shown on the parcel map as open water, but are shown on aerial photographs as marsh or wetlands. These areas are not classified or included in the town/county parcel database, but are specifically identified in the "marsh/sandbar" category in Figure IV-1 in order to distinguish them from the other unclassified parcels. It should also be noted that the parcel coverage has not been adjusted for the break in the southern barrier beach that created Esther Island from 2007 to November 2009 and that closed naturally during a late fall Nor'easter.

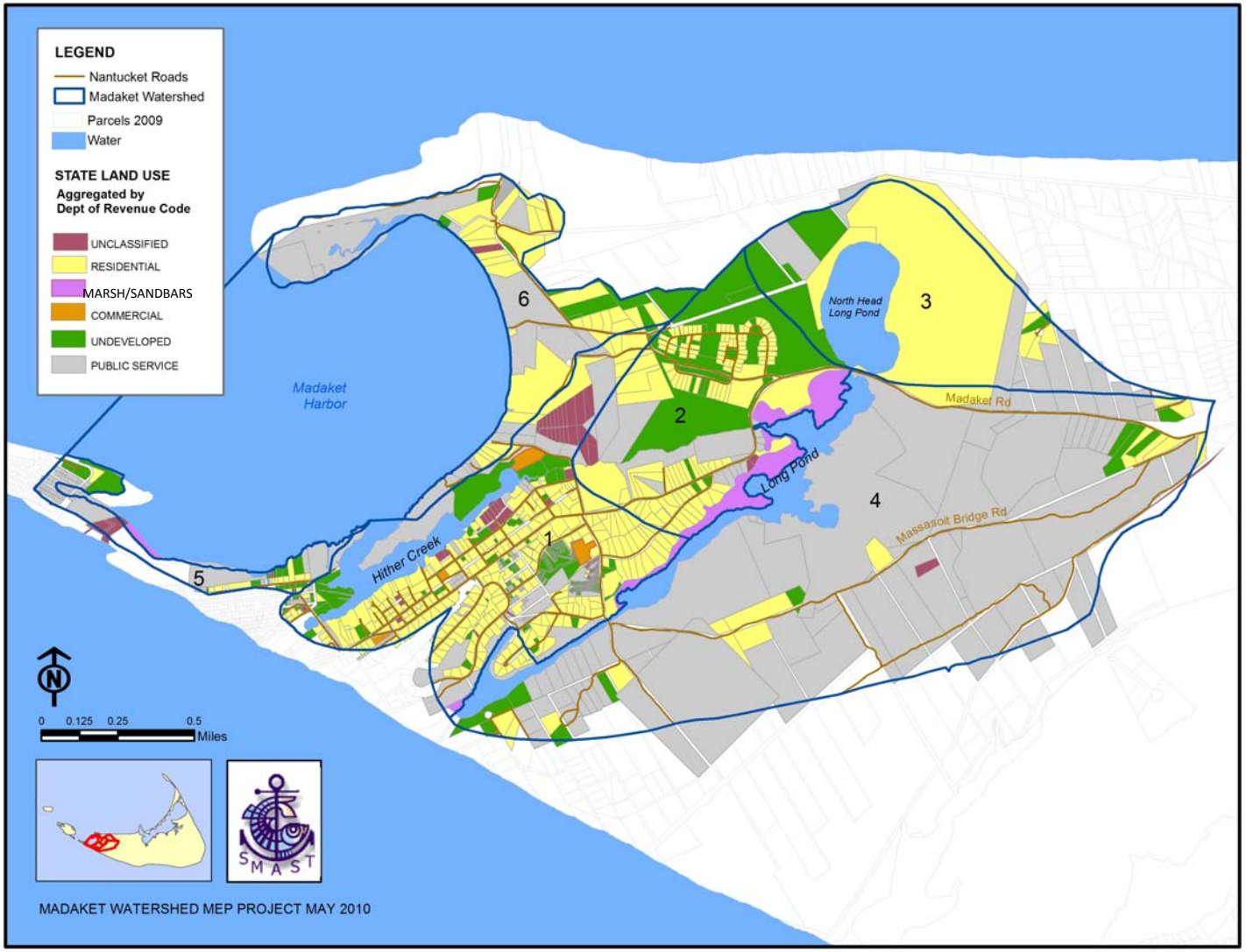

Figure IV-1. Land-use in the Madaket Harbor watershed. The watershed is completely contained within the Town of Nantucket. Land use classifications are based on 2009 assessors' records provided by the town and county and are grouped into more generalized categories used by MADOR (2008). Marsh/sandbars are a portion of the Unclassified category; these are parcels that do not have land use codes in the town/county database.

In the overall Madaket Harbor System watershed, the predominant land use based on area is public service (government owned lands, roads, and rights-of-way), which accounts for 55% of the watershed area; residential is the second highest percentage of the system watershed (28%) as depicted in Figure IV-2. The high percentage of public service lands should be expected given the large Land Bank and conservation trust/foundation land holdings in the Long Pond subwatershed. Public service lands are 91% of the area of the Long Pond subwatershed, which is 44% of the entire system watershed. Public service land uses are the dominant land use category in the sparsely developed subwatersheds (the two watersheds to the main portion of the Harbor and Long Pond), but residential is the dominant land use in the other three subwatersheds.

Residential land uses are the predominant land use if one looks at number of parcels; 51% of the parcels in the system watershed are classified as residential. Single-family residences (MADOR land use code 101) are 63% of the residential parcels in the entire system with more than half (58%) of the system watershed single-family residences in the Hither Creek subwatershed. Residential land uses vary between 6 and 67% of the subwatershed areas. Undeveloped parcels are the third highest parcel count (14%) after residential and public service in the system watershed with 10 to 28% of the parcel counts in the subwatersheds. Overall, undeveloped land uses account for 11% of the entire Madaket Harbor watershed area, while commercial properties account for 0.3% of the system watershed area.

In order to estimate wastewater flows, MEP staff generally work with municipal or water supplier partners in the study watershed to obtain parcel-by-parcel water use information that is then linked to assessor and parcel databases using GIS techniques. Only a small portion of the Madaket Harbor watershed (65 properties within Fisher's Landing) is served by public water supply. MEP staff obtained water use for this area and discussed with Bob Gardner, Superintendent of the Wannacomet Water Company (WWC) what would be an appropriate average water use for the remainder of the developed parcels that utilize private wells.

Average flow among the Fisher's Landing properties with water use accounts includes a significant seasonal impact on the number of parcels with flow and average flow among parcels with water use. During the November to May time period, a little more than half (56%) of the parcels with water accounts have measured water use, while during the June to October time period, an average of 94% of the accounts have measured water use (Figure IV-3). Water use volumes also follow a similar seasonal impact with average water use during the November to May period at 119 gallons per day (gpd), while the June to October period averages 358 gpd. After discussing with Mr. Gardner these seasonal impacts and integrating his local knowledge of water use on the Island, MEP staff assumed that June to October occupancy approximates November to May occupancy, so that much of the seasonal increase in daily water use is due to irrigation practices. This assumption appears to be confirmed by the high percentage (92%) of accounts with measured water use in October, when irrigation would be minimized, but with a significant drop in average water use from 425 gpd to 289 gpd. If most of the summer increase is irrigation, annualized average daily water use in Fisher's Landing for the purposes of estimating wastewater nitrogen loads is 89 gpd. Further discussions with Mr. Gardner confirmed that this is an appropriate average water use for properties in the Madaket Harbor watershed.

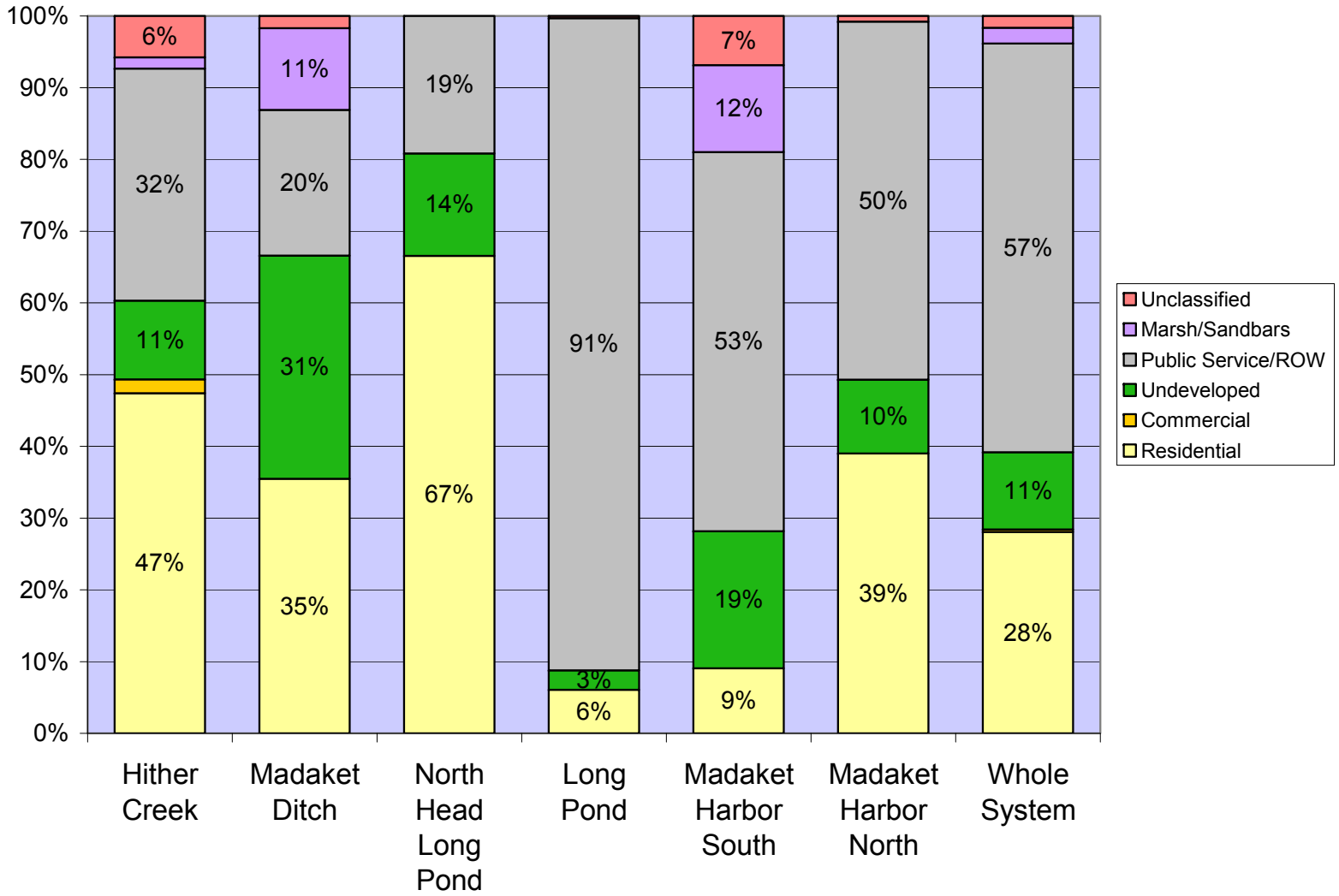

Figure IV-2. Distribution of land-uses within the subwatersheds and whole system watershed to Madaket Harbor. Only percentages greater than or equal to 3% are labeled. Generalized land use categories are based on MADOR (2008) assessor categories. Unclassified parcels do not have an assigned land use code in the town assessor database; marsh/sandbar parcels are a subset of the unclassified parcel category and are predominantly wetland/lowland areas along the western edge of Long Pond (see Figure IV-1).

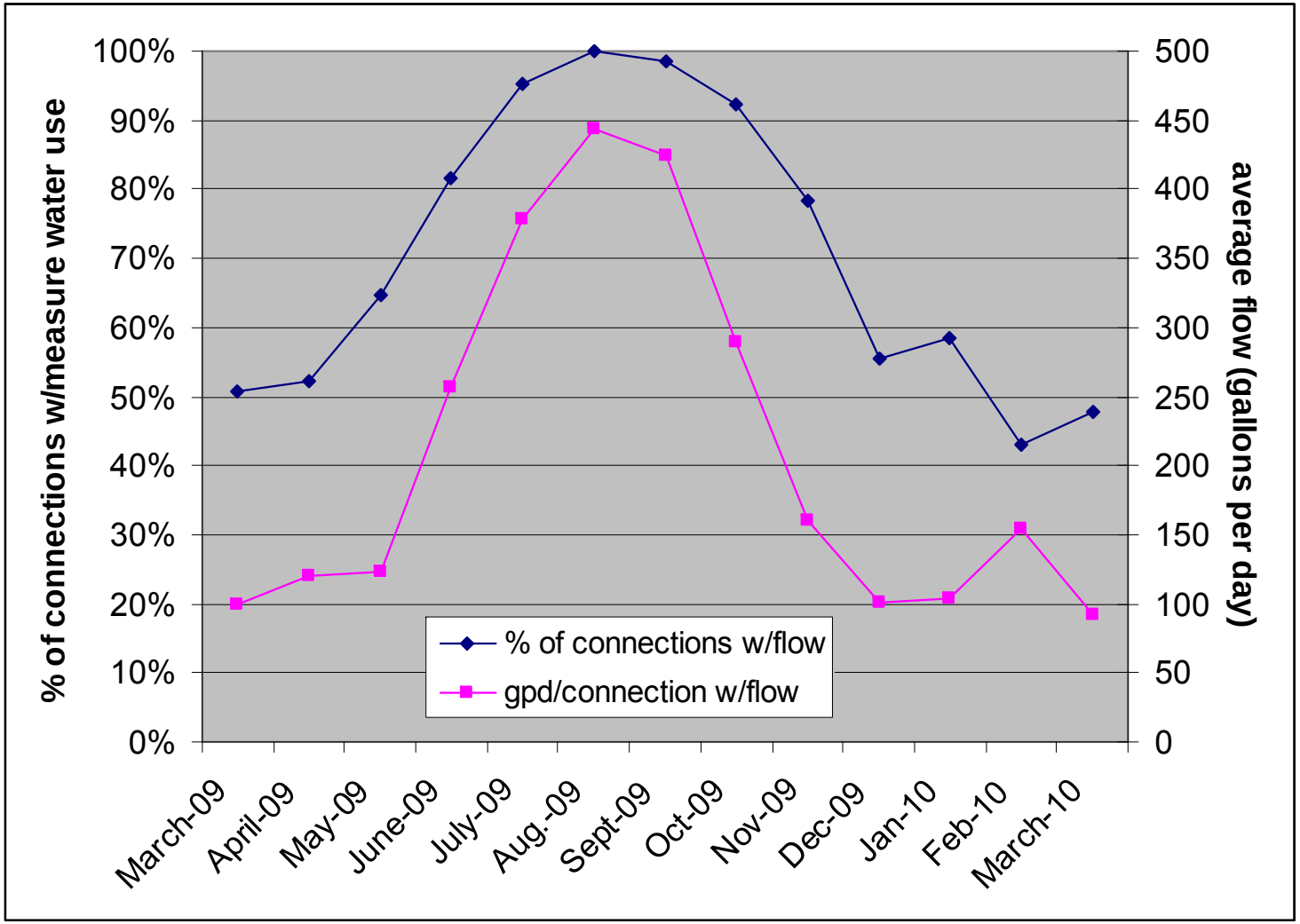

Figure IV-3. Water use in the Fisher's Landing section of the Madaket Harbor watershed (March 2009 to March 2010). Fisher's Landing includes 65 residential properties with water use accounts. Water use is average flow in gallons per day for properties with measured water use. Also shown is the percentage of properties with measured water use in each month. All data supplied by the Wannacomet Water Company (Bob Gardner, Superintendent, March 2010).

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts, decennial census data yields accurate estimates of total population only in selected watersheds. To correct for this uncertainty and more accurately assess current nitrogen loads, the MEP employs a water-use approach. The water-use approach is generally applied on a parcel-by-parcel basis within a watershed, where annual water meter data is linked to assessors parcel information using GIS techniques. The parcel specific water use data is converted to septic system nitrogen discharges (to the receiving aquatic systems) by adjusting for consumptive use (e.g. irrigation) and applying a wastewater nitrogen concentration. The water use approach focuses on the nitrogen load, which reaches the aquatic receptors 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 indicate that further nitrogen loss during aquifer transport is negligible (Robertson et al. 1991, DeSimone and Howes 1996).

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

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

The independent validation of the water quality model (Section VI) adds 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 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 Madaket Harbor System watershed, MEP staff reviewed US Census population values for the Town of Nantucket, the Census track that includes all of the Madaket watershed, and

discussed seasonal occupancy with town/county staff (Andrew Vorce, Planning Director for Town and County of Nantucket and Director of Nantucket Planning & Economic Development Commission). 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 throughout Nantucket is 2.57 people per year-round occupied housing unit with a year-round occupancy of available housing units of 40%. In contrast, Census Track 9503, which includes all areas of Nantucket west of a line drawn through the middle of Hummock Pond and extended to the northern shore of the island, has an average occupancy of 2.24 people per occupied housing unit with a 20% year-round occupancy. If the average occupancy for the whole island is multiplied by 55 gpd, the average wastewater rate for occupied units is 142 gpd, while it is 123 gpd for Census Track 9503, without correction for seasonal use.

Neither of these estimates account for the large seasonal input, however. If it is assumed that 1) the ratio of seasonal to year-round properties listed in the 2000 Census are still representative of current conditions on Nantucket, 2) the seasonal properties are occupied at the same average occupancy as year-round properties, 3) the higher seasonal occupancy occurs for 5 months (as seen in Fisher's Landing) and 4) Title 5 per capita wastewater flow of 55 gpd is appropriate, the average residential unit wastewater use for all of Nantucket would be 90 gpd and 66 gpd for the Madaket Census Track. These estimates are relatively consistent with the estimated average wastewater flow in Fisher's Landing (90% of the water use = 80 gpd). Given this analysis, MEP staff concluded that the average water use determined from the Fisher's Landing water use data provides an appropriate and accurate basis for determining wastewater nitrogen loadings within the Madaket Harbor watershed. The limited number of commercial and developed public service properties are assigned the same water/wastewater use as residential parcels. There are a total of three properties that are classified as commercial land uses in the Madaket Harbor watershed and 20 public service properties. It should be emphasized that measured water use is used as the basis for the MEP wastewater flows to avoid the necessary assumptions of seasonal occupancy rates as described above.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and cranberry bogs, with lawns being the predominant source within this category. In order to add this source to the nitrogen-loading model for the Madaket Harbor system, MEP staff reviewed available information about residential lawn fertilizing practices. No golf courses or cranberry bogs were identified within the watershed. Only residential lawns are assigned fertilizer nitrogen loads in the Madaket Harbor watershed.

Residential lawn fertilizer use has rarely been directly measured in watershed-based nitrogen loading investigations. Instead, lawn fertilizer nitrogen loads have been estimated based upon a number of assumptions: a) each household applies fertilizer, b) cumulative annual applications are 3 pounds per 1,000 sq. ft., c) each lawn is 5000 sq. ft., and d) only 25% of the nitrogen applied reaches the groundwater (leaching rate). Because many of these assumptions had not been rigorously reviewed in over a decade, 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 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. The MEP fertilizer leaching rate of 20% recently received a detailed review prepared by Horsley Witten Group Inc. The task was to independently determine a nitrogen fertilizer leaching rate from turf grass specific to the permeable soils typical of the watersheds to southeastern Massachusetts estuaries and then compare it to the MEP analysis. The analysis used both the results of previous studies and new data collected subsequent to the initiation of the MEP. The results indicated a leaching rate of 19% and the study concluded that "the MEP leaching rate estimate of 20% is reasonable (Horsley Witten Group, 2009). It is likely that the MEP fertilizer contribution represents a conservative estimate of nitrogen load from residential lawns as professionally maintained lawns have been found to have higher fertilizer application rates and hence a higher estimated loss to groundwater of 3 lb/lawn/yr.

Nitrogen Loading Input Factors: Landfill

The Nantucket landfill is located off Madaket Road in the Long Pond watershed (Figure IV-4). The landfill is now part of an integrated waste management system at the site that includes a digester, composting and mining of portions of the landfill. A well network surrounds the landfill and these wells are sampled quarterly as part of compliance monitoring required by MassDEP. MEP staff obtained data from this groundwater monitoring data collected 2004 and 2009 (personal communication, Andrew Vorce, Planning Director for Town and County of Nantucket and Director of Nantucket Planning & Economic Development Commission, March 2010).

This groundwater monitoring data includes nitrate-nitrogen, alkalinity, chloride, and other inorganic measures, but does not include total nitrogen measurements or other components of total nitrogen, such as ammonium-nitrogen data. Based on a previous review of monitoring data from the groundwater plume associated with the Town of Brewster landfill (Cambareri and Eichner, 1993), MEP staff determined a relationship between ammonium-nitrogen and alkalinity concentrations (NH4-N = 0.0352*ALK - 0.3565; r2 = 0.82). This relationship was used to estimate ammonium-nitrogen concentrations from the available landfill monitoring data. Although nitrate-nitrogen and ammonium-nitrogen concentrations are not a complete measure of all nitrogen species, landfills do not tend to release significant portions of dissolved organic nitrogen (Pohland and Harper, 1985).

Based on the water quality review and estimated ammonium-nitrogen, MEP staff determined average ammonium-N plus nitrate-N concentrations in two wells (MW-3S and MW-4S) in the predominant flow path down gradient of landfill at 9.4 ppm. This high concentration is consistent with other measurements in the wells, including elevated average specific conductance (both average >800 µmhos/cm) and low dissolved oxygen (1.6 and 0.9 ppm, respectively). MEP staff discussed this assessment with Jeff Willett, Town and County of Nantucket, Department of Public Works, who also noted that a historic disposal area for animal carcasses is also located along the western edge of the landfill and may be contributing to the water quality impacts. Using estimates of the area of solid waste, MEP staff developed an estimated annual total nitrogen load of 777 kg from the Nantucket landfill.

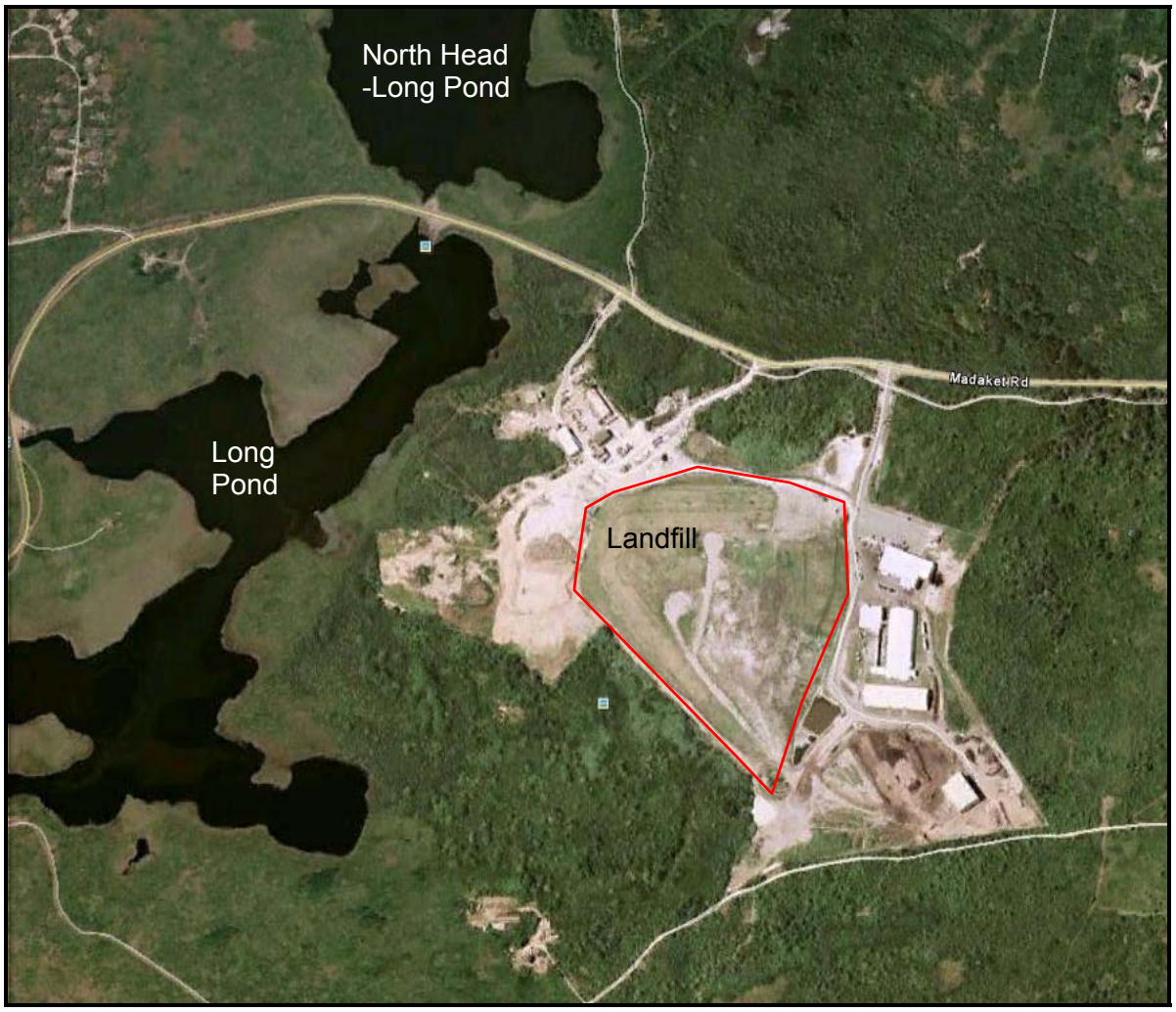

Figure IV-4. Nantucket Landfill and proximity to upper Long Pond. The landfill is directly up gradient and in the groundwater watershed to Long Pond. Red outline shows the approximate area of solid waste. Groundwater monitoring data provided by the Town and County of Nantucket, collected between 2004 and 2009 provided the basis for estimating total nitrogen load from the landfill. Base map courtesy of Google Earth (June 2010).

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the Cape Cod Commission's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and Massachusetts DEP's Nitrogen Loading Computer Model Guidance (1999). The recharge rate for natural areas and lawn areas is the same as utilized in the MEP-USGS groundwater modeling effort on Cape Cod (Section III). Factors used in the MEP nitrogen loading analysis for the Madaket Harbor watershed are summarized in Table IV-1.

Table IV-1. Primary Nitrogen Loading Factors used in the Madaket Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Nantucket data.

Nitrogen Concentrations:	mg/l	Recharge Rates:	in/yr
Road Run-off	1.5	Impervious Surfaces[2]	42
Roof Run-off	0.75	Natural and Lawn Areas	27.25
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:	
Natural Area Recharge	0.072	Existing water use for developed parcels and buildout parcels:	89 gpd
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (ft^2)[1]	5,000	No commercial or industrial additions assumed at buildout	
Residential Watershed Nitrogen Rate (lbs/lawn) [1]	1.08		

[1]Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.
[2]Based on average precipitation @ Nantucket Airport (1961 - 1990)

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, parcels were assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel was located within a respective watershed. Following the assigning of boundary parcels, all large parcels were examined individually and were split (as appropriate) in order to obtain less than a 2% difference between the total land area of each subwatershed and the sum of the area of the parcels within each subwatershed. The resulting creation of "parcelized" watersheds to Madaket Harbor are shown in Figure IV-5.

The review of individual parcels straddling watershed boundaries included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Individualized information for parcels with atypical nitrogen loading (landfill, condominiums, etc.) was also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the down-gradient estuary. The assignment effort was undertaken to better define the sub-embayment loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

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

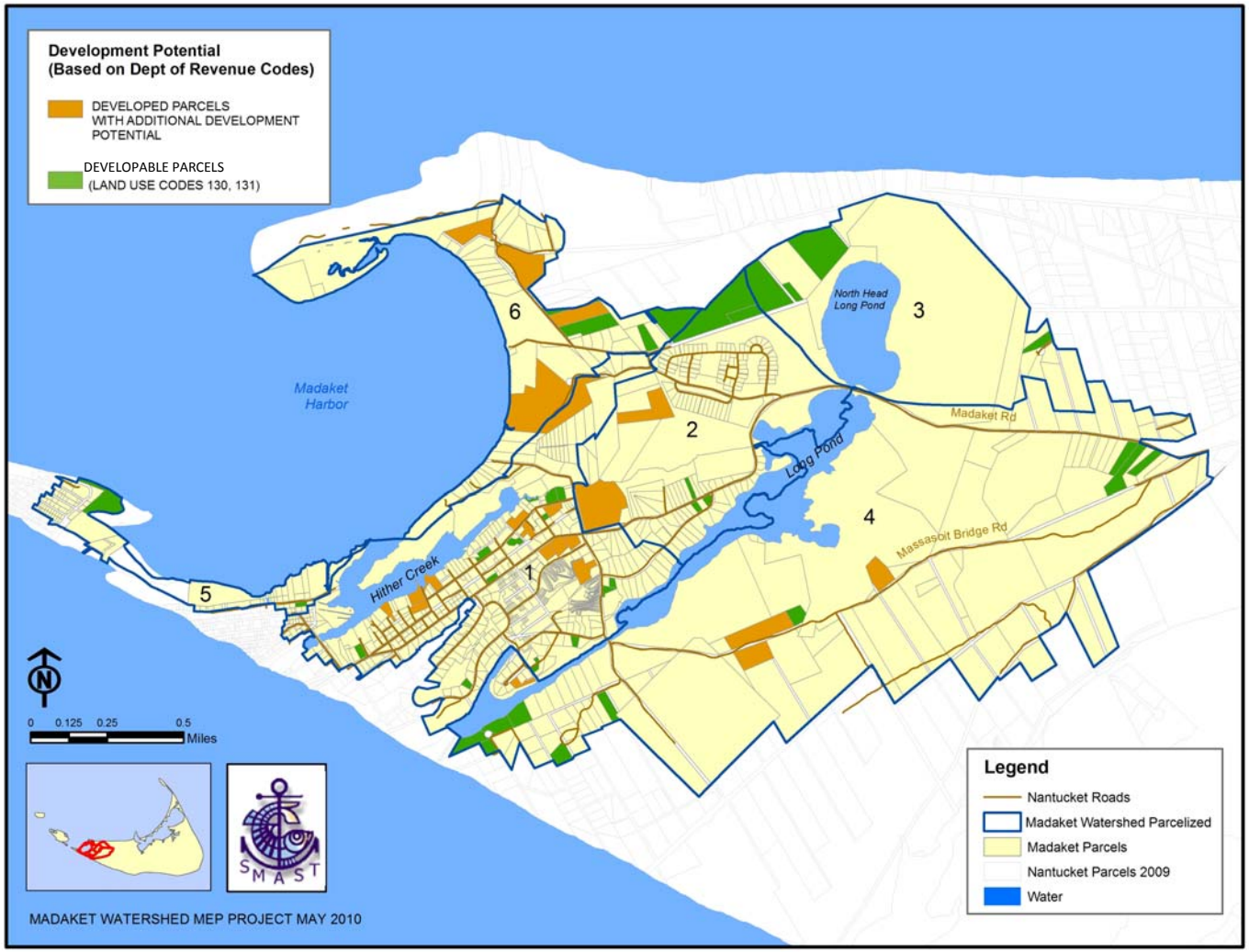

Figure IV-5. Parcels, Parcelized Watersheds, and Developable Parcels in the Madaket Harbor watersheds. Parcels colored orange are developed parcels with additional development potential based on existing zoning, while parcels colored green are undeveloped parcels classified as developable for residential land uses by the town assessor. The parcelized watershed is drawn to minimize the division of properties for management purposes while achieving a match of area with the watersheds of 2% or less.

For management purposes, the aggregated embayment watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Madaket Harbor watershed, the major types of nitrogen loads are: wastewater (i.e., septic systems), the Nantucket landfill, fertilizer (i.e., residential lawns), impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-6). 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. Natural nitrogen attenuation does not occur in the Madaket Harbor - Long Pond watershed as there are no significant freshwater streams or ponds, so all subwatershed nitrogen loads are transported and directly discharge to the estuary via groundwater.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment (or scenario) of potential development within the study area watershed. For the Madaket Harbor modeling, MEP staff reviewed individual properties for potential additional development and then corrected this initial assessment based on consultation with Town and County of Nantucket planners (Andrew Vorce and Leslie Snell, personal communication). This buildout review included assessment of minimum lot sizes based on current zoning and potential additional development on existing developed lots.

The buildout procedure used in this watershed and generally completed by MEP staff is to evaluate town zoning to determine minimum lot sizes in each of the zoning districts, including overlay districts (*e.g.*, water resource protection districts). Larger lots are subdivided by the minimum lot size to determine the total number of new lots. In addition, existing developed properties are reviewed for any additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence are assumed to have one additional residence at buildout. Most of the focus of new development is for properties classified as developable by the town assessor (e.g., state class land use codes 130 and 131 are assigned to developable residential properties). Properties classified by the town assessors as “undevelopable” (e.g., codes 132 and 392) were not assigned any development at buildout. Commercial and industrial developable properties are not subdivided; the area of each parcel and the factors in Table IV-1 were used to determine a wastewater flow for these properties.

Based on the buildout assessment completed for this review, there are 116 potential additional residential dwellings in the Madaket Harbor watershed. There is no additional commercial development; no industrial development exists in the watershed and none is available under current zoning. The addition of the 116 residential properties would represent a 21% increase over the current number of properties classified as residential properties. All parcels included in the buildout assessment of the Madaket Harbor watershed are shown in Figure IV-6.

Table IV-2 includes a column that presents a sum of the additional nitrogen loads by subwatershed for the buildout scenario. This sum includes the wastewater, fertilizer, and impervious surface loads from additional residential dwellings yet to be constructed. The Madaket Harbor - Long Pond watershed is approaching build-out so that present projections of buildout additions suggest an increase in the present unattenuated watershed nitrogen loading rate of only 15%.

Table IV-2. Madaket Harbor System (Madaket Harbor, Hither Creek, Madaket Ditch and Long Pond) Nitrogen Loads. Present annual nitrogen loading represents current conditions. Buildout nitrogen loads are based on projections of additional development allowed relative to current zoning minimum lot sizes. All values are kg N yr^{-1}.

		Madaket Harbor N Loads by Input (kg/y):							% of Pond Outflow	Present N Loads			Buildout N Loads		
Watershed Name	Watershed ID#	Wastewater	Landfill	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Madaket Harbor System		1904	777	272	346	4128	387	453		7814		7814	8267		8267
Hither Creek	1	1061		167	163	26	56	125		1475		1475	1600	0	1600
Hither Creek Estuary Surface						195				195		195	195		195
Madaket Ditch Total		703	777	81	154	766	281	250		2762		2762	3012		3012
Madaket Ditch	2	551		61	70	158	47	137		888		888	1025	0	1025
Long Pond	4	125	777	16	79	0	181	62		1179		1179	1241	0	1241
Long Pond Estuary Surface						356				356		356	356		356
North Head Long Pond		26	0	4	5	253	52	51		340		340	390		390
North Head Long Pond	3	26		4	5	0	52	51		87		87	138	0	138
North Head Long Pond Estuary Surface						253				253		253	253		253
Madaket Harbor South	5	47		8	3	0	11	16		69		69	84	0	84
Madaket Harbor North	6	93		16	26	0	39	62		173		173	236	0	236
Harbor Surface Area						3140				3140		3140	3140		3140

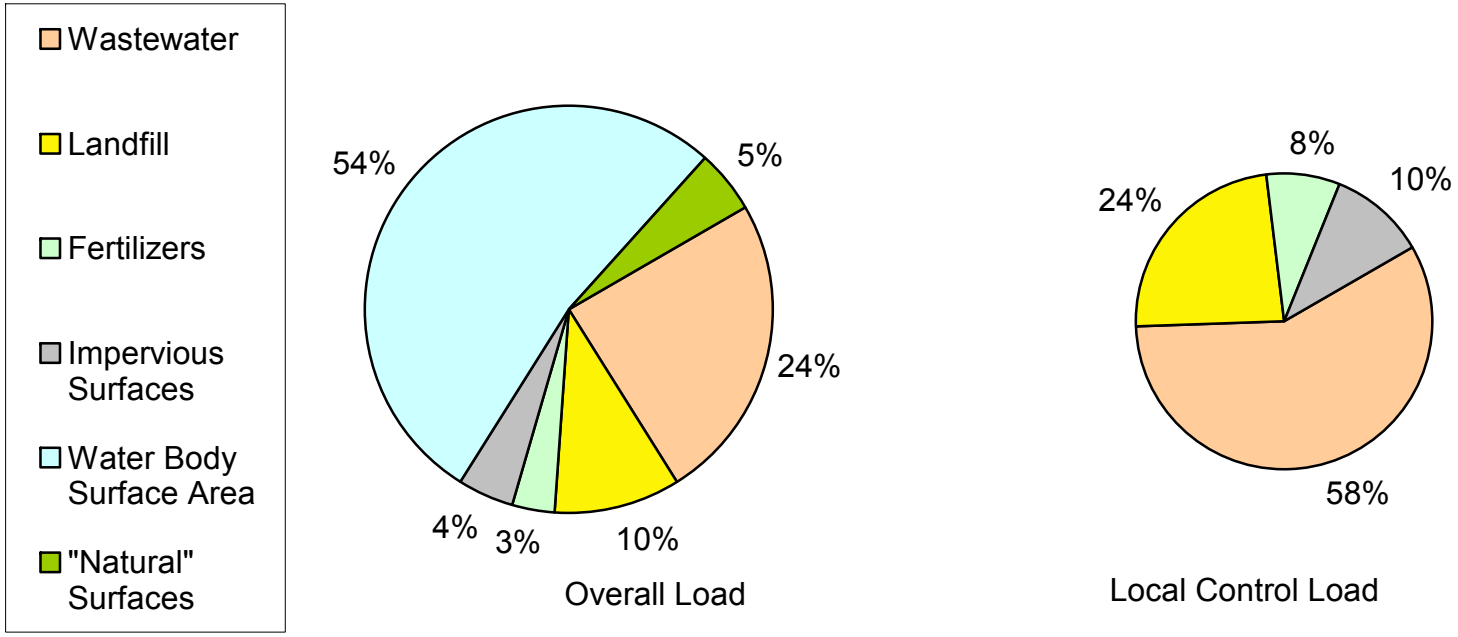

Figure IV-6. Land use-specific unattenuated nitrogen load (by percent) to the overall Madaket Harbor System watershed. "Overall Load" is the total nitrogen input within the watershed including atmospheric deposition to the estuary and nitrogen from natural surfaces (forests, grassland, etc), while the "Local Control Load" represents those nitrogen sources that could potentially be under local regulatory control.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out or sewering analysis) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the watershed of the Madaket Harbor - Lagoon Pond Estuarine System were based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1). If all of the nitrogen applied or discharged within a watershed reaches an embayment, the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport is 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. This is the case for the watershed of the Madaket Harbor - Long Pond Estuary. Unlike most watersheds in southeastern Massachusetts, nitrogen does not pass through a surface water ecosystem on its path to the adjacent embayment. It is in these surface water systems that have the needed conditions for nitrogen retention and denitrification. As there were no streams or great fresh ponds within the Madaket Harbor - Long Pond watershed, the watershed loading approach considered that nitrogen reaching the water table was transported without attenuation in the groundwater system until discharge to the estuary.

While there was no freshwater attenuation of nitrogen within the watershed of this system, stream flow measurements were still conducted in an effort to confirm the watershed delineation to the North Head of Long Pond as well as the overall Long Pond system. The standard MEP stream gauging approach was used to determine the volumetric flow from the North Head of Long Pond to Long Pond (with necessary adjustments for salinity). However, this approach was not as appropriate for determining flows from Long Pond into Madaket Ditch, due to the high degree of tidal influence and the lack of a clear relation between stage in Madaket Ditch (influenced by tide and weather) and flow. As a result an estimate of average flow into Madaket Ditch from Long Pond was calculated based on the ratio between flow measurements made at the culvert separating the North Head of Long Pond from the main Long Pond Basin and flow measurements made at low tide in Madaket Ditch, necessarily correcting for salinity at both locations. Overall, stage and flow measurements were undertaken at the upper and lowermost gage deployment locations the Long Pond / Madaket Ditch system (Figure IV-7). The uppermost (North Head of Long Pond) gage and the lowermost (Madaket Ditch) gage were deployed simultaneously and recorded from June 2003 through September 2005. The intermediate gage located where Long Pond discharges to the top of Madaket Ditch was deployed for a shorter period (January 2005 to September 2005) to supplement the hydrodynamic field data collection effort for Long Pond. Velocity profiles at each gage site were conducted every month to two months.

During the gage deployment period limited flow measurements were obtained at times when the culvert passing water from Long Pond to Madaket Ditch was not over-topped. Due to the degree to which the tide influences Madaket Ditch, Long Pond and the North Head of Long Pond, a valid stage-discharge relationship could be developed only for the uppermost gage location. Water samples were also collected at the Madaket Ditch gage location furthest down gradient in the system in order to provide for a salinity correction to estimate freshwater discharge from total volumetric flow. Determination of flow at each gage was calculated and based on the measured values obtained for “stream” cross sectional area and velocity.

Discharge was represented by the summation of individual discharge calculations for each channel or culvert subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire cross section were not averaged and then applied to the total stream cross sectional area.

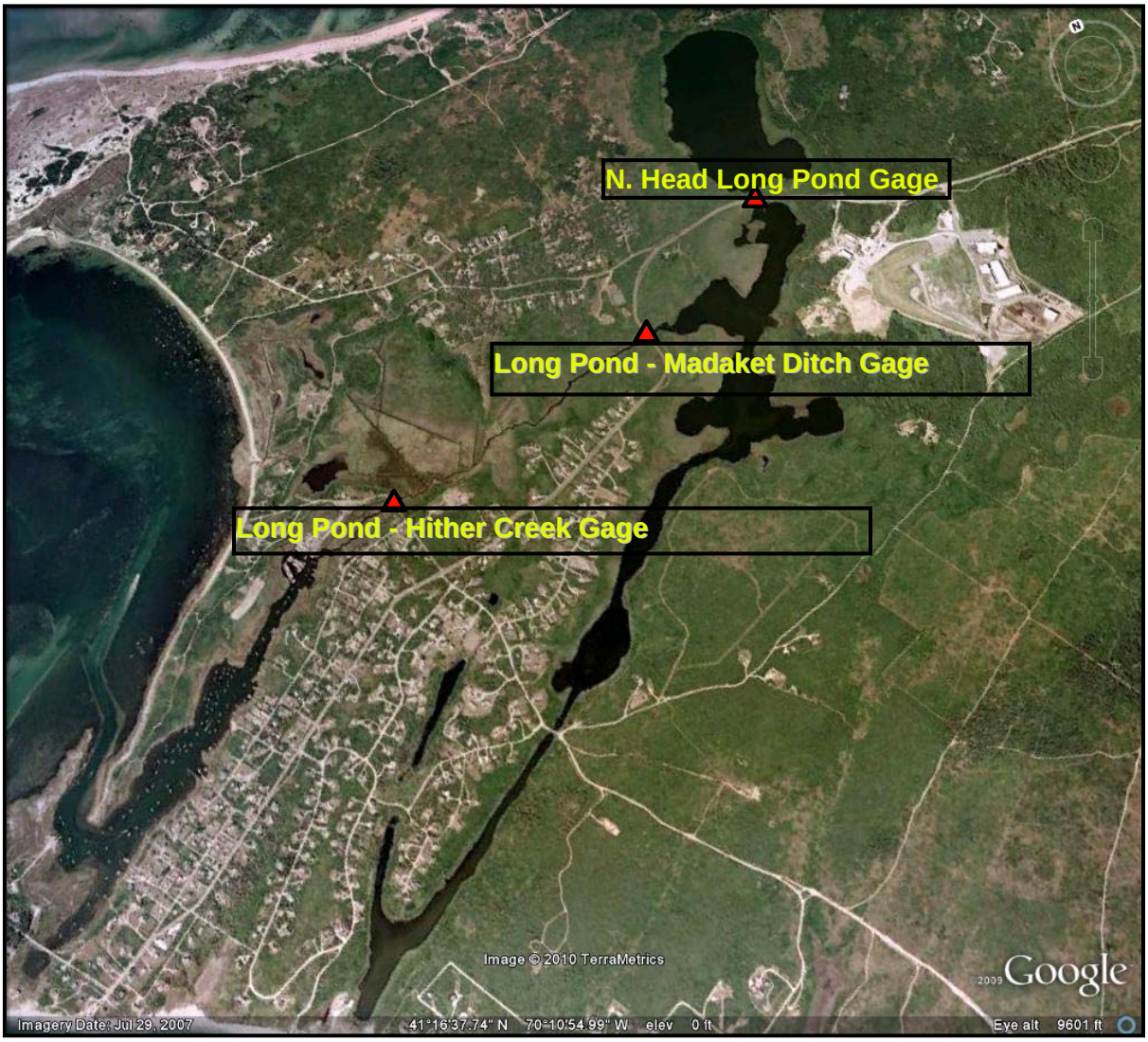

Figure IV-7. Location of gages for measurement of stage for calculating freshwater flows throughout the Long Pond / Madaket Ditch surface water system. Flows at all three gage locations were tidally influenced limiting the development of stage –discharge relationships for determining average daily flows from Long Pond to Hither Creek via Madaket Ditch.

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 channel or culvert subsection will have a calculated discharge value and the summation of all the sub-sectional channel/culvert discharge values will be the total calculated discharge at a given point in the system.

Due to the degree of tidal influence at the lowermost gage positioned in Madaket Ditch just prior to discharging to Hither Creek, the flow measurements could not be combined with measurements of stage in order to determine a classic stage – discharge relation for calculating daily flows at the gage location. As such, the measurements of flow were adjusted as best as possible for salinity influence and utilized along with the measured flows at the North Head of Long Pond to get a ratio between the flows. This ratio was applied to the flow record at the North Head of Long Pond which was obtained using an MEP developed rating curve to then calculate the daily flows at the gage location in Madaket Ditch and generally check the watershed delineations to Long Pond.

Since tidal influence was less of a factor at the gage located between the North Head of Long Pond and Long Pond, at that gage, a stage – discharge relation was developed to calculate daily flow of water from the North Head of Long Pond to Long Pond. Periodic measurement of flows over the entire gage 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 gage located in the North Head of Long Pond immediately up-gradient of the culvert passing under the road separating the North Head from Long Pond proper. Water level data obtained every 10-minutes was averaged to obtain hourly stages at the culvert. These hourly stage values are typically entered into the stage-discharge relation to compute hourly flow and then the hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. However, as a result of the tidal influence on stage measured by the gage, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of the freshest water flow. The lowest tide stage values for any given day were extracted from the overall stage record and utilized in the stage – discharge relation in order to compute daily flow. A complete annual record of stream flow (365 days) was generated for the discharge flowing from the North Head of Long Pond into Long Pond. The annual flow record for the water flow at the gage in the North Head of Long Pond was utilized to confirm the watershed delineation to the North Head of Long Pond and the Madaket Ditch freshwater outflow was used to calculate the delineation of the total subwatershed area which contributes freshwater to the gage site, e.g. North Head of Long Pond, Long Pond plus Madaket Ditch.

IV.2.1 Surface water Freshwater Discharge: Long Pond Discharge to Hither Creek via Madaket Ditch

Long Pond, located up gradient of the Madaket Ditch gage site (N. Cambridge Street road crossing) is a large brackish to freshwater pond (depending on distance away from the culvert and is hydraulically connected to Madaket Harbor via Hither Creek and Madaket Ditch, which is the narrow tidal creek to Long Pond. This “stream” outflow via Madaket Ditch, allows for a direct measurement of the subwatershed freshwater discharge to the estuary, hence a mechanism for confirming the contributing watershed area.

At the Madaket Ditch gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water (stage). All of the Madaket Ditch channel from the head of Hither Creek to its entry into Long Pond is tidally influenced. To confirm the degree of salinity influence on the “freshwater” flow measurements, the stage record was analyzed for any

semi-diurnal variations indicative of tidal influence and salinity measurements were conducted on weekly water samples collected from the gage site. Average low tide salinity was determined to be 8.7 ppt. indicating that the freshwater flow estimates would require correction for salinity. In addition, the extent of tidal influence precluded the development of a stage/discharge relationship (rating curve) at this site, MEP staff used the salinity adjusted flow measurements to develop a ratio between flow in Madaket Ditch and flow out of the North Head of Long Pond where a rating curve was developed. The development of the rating curve and determination of daily flow using the stage record at the North Head of Long Pond followed all the standard MEP stream gauging procedures.

Calibration of the gage in both Madaket Ditch and the North Head of Long Pond was checked approximately monthly each time the sites were visited to make flow measurements and download the instruments. The gages in both Madaket Ditch and the North Head of Long Pond were installed on June 2, 2003 and were set to operate continuously for at least 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued until September 14, 2005 for a total deployment of 27 months. This long deployment period was needed due to instrument failures and vandalism. Ultimately, one complete hydrologic year was obtained (September 1, 2004 to August 31, 2005).

Surface flow (volumetric discharge) at both the Madaket Ditch gage location and the North Head of Long Pond location was measured every 4 to 8 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the North Head of Long Pond site based upon these flow measurements and measured water levels at the gage site, since this was the least tidally influence location and the site most likely to yield a useable rating curve. The rating curve was then used for conversion of the continuously measured stage data to obtain an estimate of the daily freshwater flow volume using the appropriate salinity correction. Even at this location, the average low tide salinity for the samples of flow between the North Head and Long Pond was 7.9 ppt. Measured flow was salinity adjusted using the average "stream" sample salinity and a boundary salinity from water data collected at the nearest Long Pond sampling station as well as from samples of water leaving Long Pond. Using the rating curve developed for the gage at the North Head of Long Pond and the salinity adjustment, it was determined that the annual flow of water leaving the North Head of Long Pond and entering Long Pond was 952,285 m3/yr (2,603 m3/d). This compared relatively well with the calculated flow based on recharge and watershed area (730,000 m3/yr / 2,000 m3/d) and therefore the annual flow record from the North Head of Long Pond was subsequently utilized to determine the daily flows in Madaket Ditch flowing into Hither Creek. A similar water balance approach was utilized based on the watershed delineations previously discussed in Section III to confirm long-term average freshwater discharge expected at the Madaket Ditch gage site.

The annual freshwater flow record for Madaket Ditch was calculated using a ratio developed from salinity adjusted measured flows at the North Head of Long Pond gage location and the measured flows at the Madaket Ditch gage location. Using a ratio of 1:4.52 (N. Head flow to Hither Creek flow) the MEP determined the annual flow from Madaket Ditch to Hither Creek to be 4,303,715 m3/yr at the gage location. The measured "freshwater" discharge from Madaket Ditch was 5% above the water balance estimate based upon the watershed delineation. The average daily flow based on the MEP calculated flow data for one hydrologic year beginning September 2004 and ending in August 2005 (low flow to low flow) was 11,791 m^3/day compared to the long term average flows determined by the USGS modeling effort (11,242 m^3/day) based upon the contributing area. The negligible difference between the long-term average flow based on the watershed area and the MEP measured flow indicate that the delineated watershed area is accurate (Figure IV-8, Table IV-3).

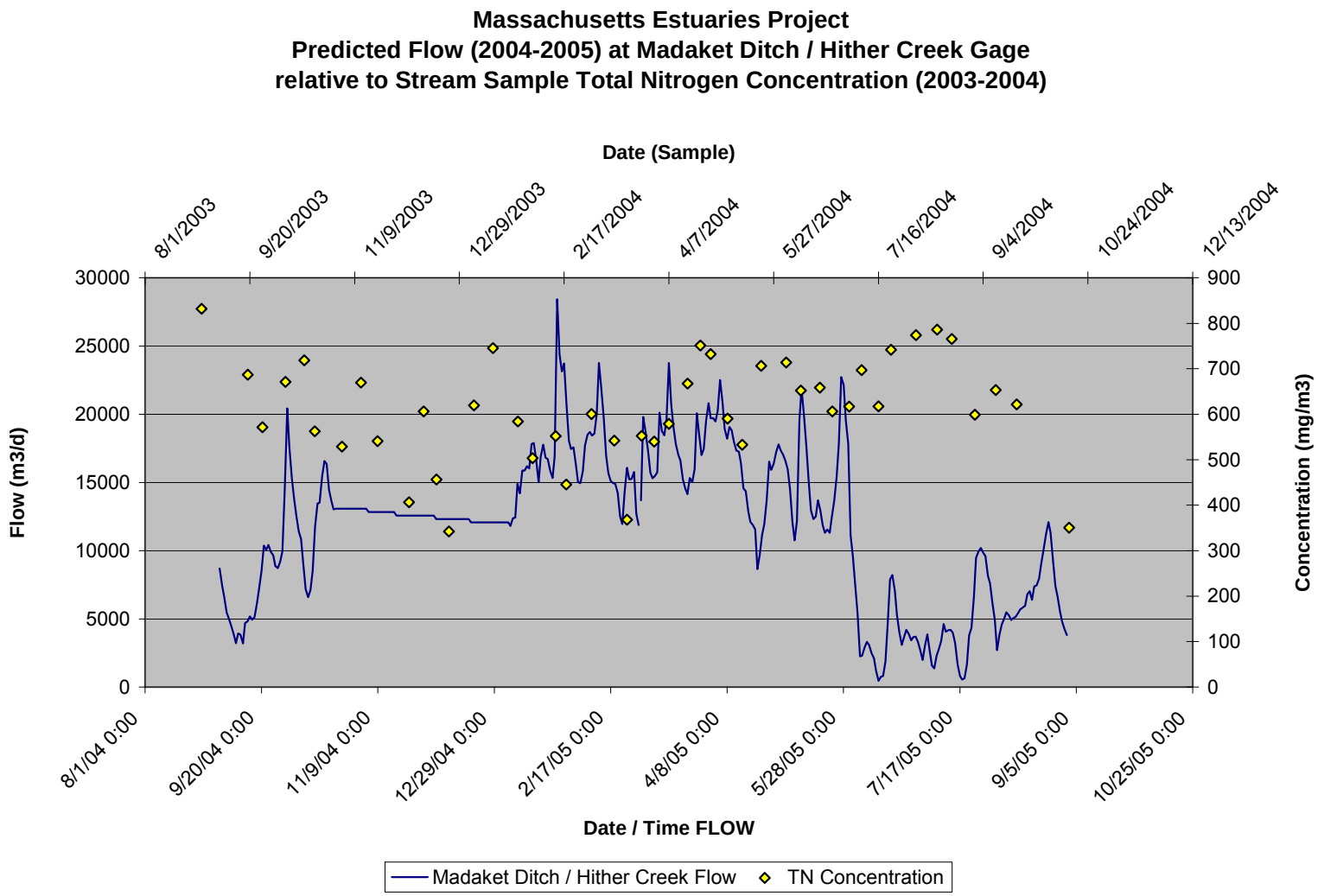

Figure IV-8. Madaket Ditch discharge (solid blue line) and total nitrogen (yellow symbols) concentrations for determination of annual volumetric discharge and nitrogen concentrations from the watershed to Long Pond / Madaket Ditch. Flat portion of plot is the result of an instrument failure.

Table IV-3. Summary of annual volumetric discharge from the North Head of Long Pond and Madaket Ditch flowing into Hither Creek. Nitrogen load is only an estimate as nitrogen data was not available for the same time period as the gage record.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
North Head of Long Pond Culvert MEP Determined Flow	**September 1, 2004 to August 31, 2005**	**952,285**	**--**	**--**
North Head of Long Pond Culvert CCC Determined Flow	Based on Watershed Area and Recharge	**730,000**	--	--
Madaket Ditch @ N. Cambridge Street Madaket Ditch MEP	**September 1, 2004 to August 31, 2005**	**4,303,715**	**156**	**2,392**
Madaket Ditch @ N. Cambridge Street Madaket Ditch (CCC)	Based on Watershed Area and Recharge	**4,103,330**	--	--

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

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

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

As stated in above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the Madaket Harbor and Long Pond System predominantly in highly bio-available forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bio-available form nitrate. This nitrate and other bio-available forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like Atlantic Ocean or Nantucket Sound). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with their associated nitrogen “load” become incorporated into the surficial sediments of the 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 enclosed tributary basins, particularly if they are deeper than the adjacent embayment. To some extent, the settling characteristics can be evaluated by observation of the grain-size and organic content of sediments within an estuary.

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bio-available nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with deep depositional basins or salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh or Sesechacha Pond). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, for example in the margins of the main basin

to Lewis Bay in the Town of Barnstable. In contrast, most embayments show low rates of nitrogen release throughout much of basin area and in regions of high deposition typically support anoxic sediments with high release rates during summer months. The consequence of high deposition rates is that the basin sediments are unconsolidated, organic rich and sulfidic in nature (MEP field observations).

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading to the Madaket Harbor and Long Pond System. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for Determining Sediment-Watercolumn Nitrogen Exchange

For the Madaket Harbor and Long Pond Embayment System, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples (24 cores) were collected from 23 sites (Figure IV-9 and IV-10) in July-August 2003, focusing on the main central basins, which account for most of the bottom area of the Harbor and Long Pond. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab situated at a private residence on the shore of Madaket Harbor. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The number of core samples from each site (Figure IV-9 and IV-10) per incubation are as follows:

Madaket Harbor Main Basin - Benthic Nutrient Regeneration Cores

- MAD-1 1 core (Main Harbor Basin)
- MAD-2 1 core (Main Harbor Basin)
- MAD-3 1 core (Main Harbor Basin)
- MAD-4 1 core (Main Harbor Basin)
- MAD-5 1 core (Main Harbor Basin)
- MAD-6 1 core (Main Harbor Basin)
- MAD-7 1 core (Main Harbor Basin)
- MAD-8 1 core (Main Harbor Basin)
- MAD-14 1 core (Main Harbor Basin)
- MAD-15/16 2 cores (Main Harbor Basin)

Hither Creek- Benthic Nutrient Regeneration Cores

- MAD-9 1 core (Uppermost Marina Basin)
- MAD-10 1 core (Main Channel)
- MAD-11 1 core (Main Channel)
- MAD-12 1 core (Lower Creek)
- MAD-13 1 core (Inlet to Hither Creek)

Long Pond - Benthic Nutrient Regeneration Cores

- LPN-1 1 core (North Head Long Pond)
- LPN-2 1 core (North Head Long Pond)
- LPN-3 1 core (Long Pond)
- LPN-4 1 core (Long Pond)
- LPN-5 1 core (Long Pond)
- LPN-6 1 core (Long Pond)
- LPN-7 1 core (Long Pond)
- LPN-8 1 core (Long Pond)

Figure IV-9. Madaket Harbor System (inclusive of Hither Creek) locations (yellow diamonds) of sediment sample collection for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-3.

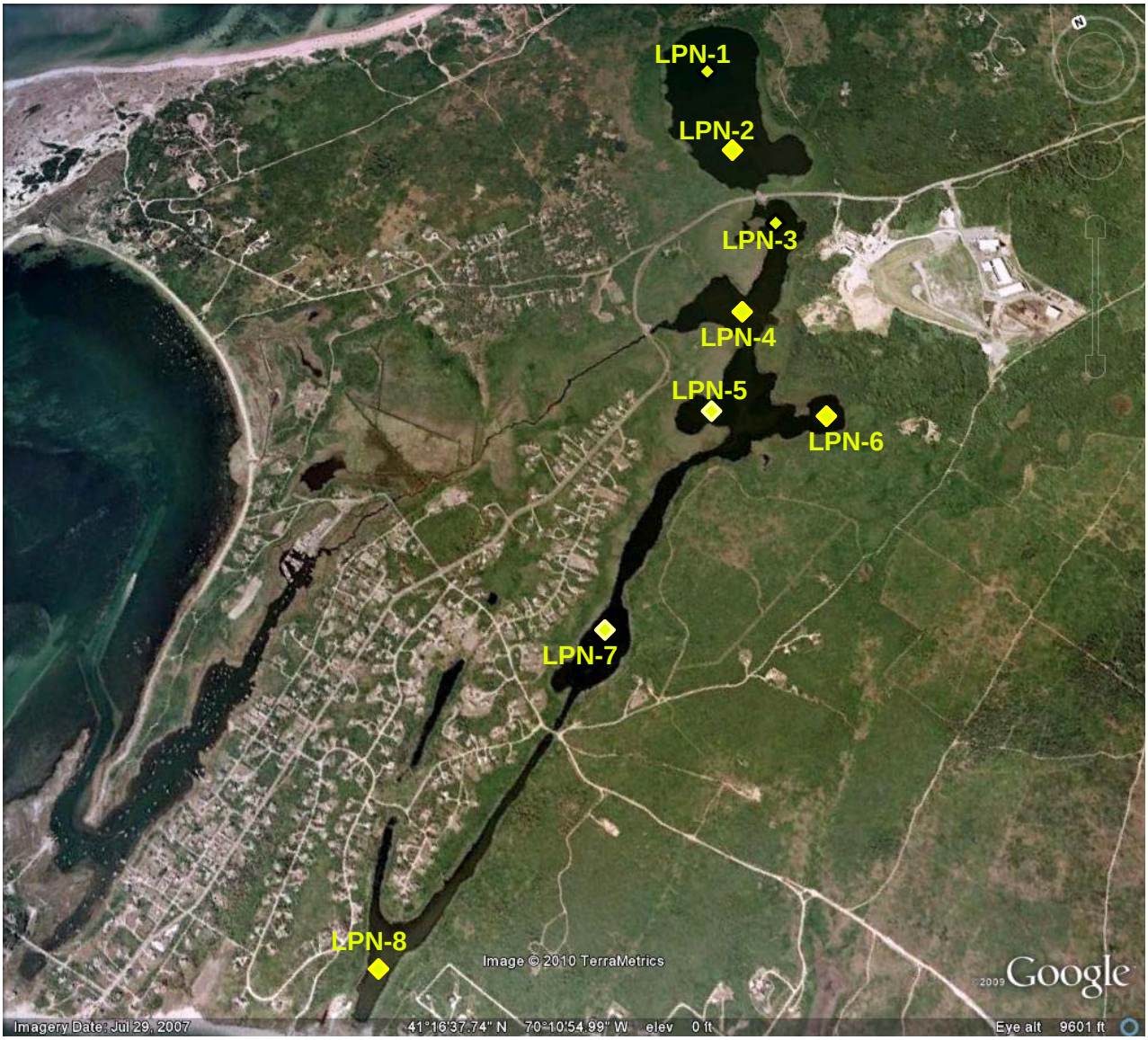

Figure IV-10. Long Pond locations (yellow diamonds) of sediment sample collection for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-3.

Sampling was distributed throughout the primary estuarine basins of this system: the central portion of Madaket Harbor; plus the main tributary channel of Hither Creek as well as Long Pond (inclusive of the North Head of Long Pond). For each distinct "basin" the results for each site were combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

Sediment-water column exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1998) for nutrients and metabolism. Upon return to the field laboratory (private residence on the shore of Madaket Harbor), the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and ortho-phosphate (Murphy

and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-20°C) for assay of nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON (D'Elia *et al.* 1977). Rates were determined from linear regression of analyte concentrations through time.

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

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

Water column nitrogen levels are the balance of inputs from direct sources (land, rain etc), losses (denitrification, burial), regeneration (water column and benthic), and uptake (e.g. photosynthesis). As stated above, during the warmer summer months the sediments of shallow embayments typically act as a net source of nitrogen to the overlying waters and help to stimulate eutrophication in organic rich systems. However, some sediments may be net sinks for nitrogen and some may be in “balance” (organic N particle settling = nitrogen release). Sediments may also take up dissolved nitrate directly from the water column and convert it to dinitrogen gas (termed “denitrification”), hence effectively removing it from the ecosystem. This process is typically a small component of sediment denitrification in embayment sediments, since the water column nitrogen pool is typically dominated by organic forms of nitrogen, with very low nitrate concentrations. However, this process can be very effective in removing nitrogen loads in some systems, particularly in streams, ponds and salt marshes, where overlying waters support high nitrate levels. In estuarine sediments most denitrification in sediments occurs as settled organic particles decompose and released ammonium is oxidized to nitrate. Some of this nitrate "escapes" to the overlying water and some is denitrified within the sediment column. Both pathways of denitrification are at work within the Madaket Harbor-Long Pond 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-11).

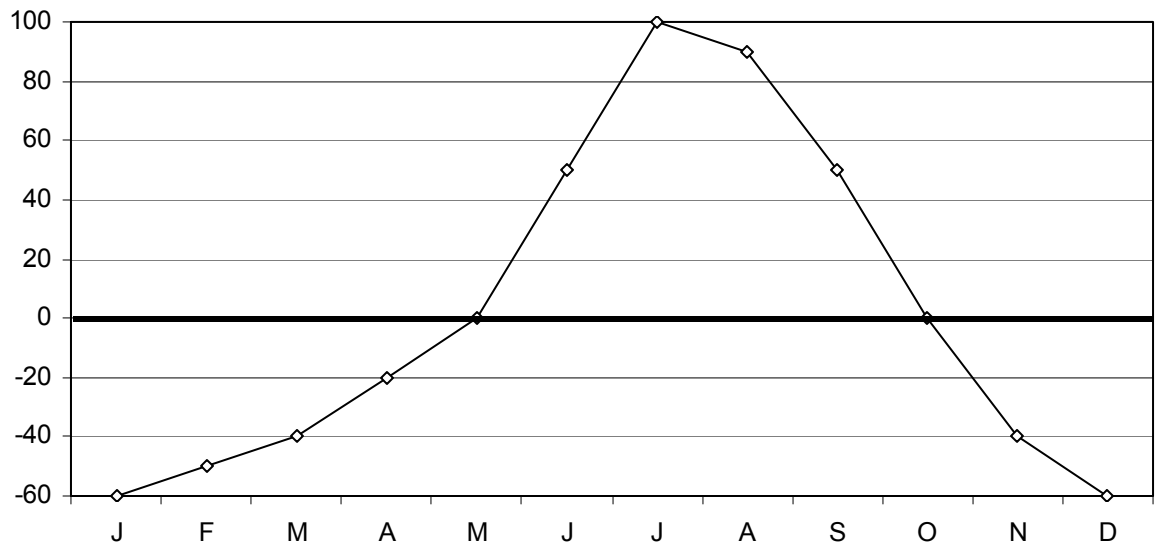

Figure IV-11. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

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

Sediment sampling was conducted throughout the primary embayment basins of the Madaket Harbor - Long Pond Embayment System in both the open water portion of the Harbor which encompasses both the area with direct exchange with clean Nantucket Sound / Atlantic Ocean water as well as the Hither Creek basin, influenced by discharge of lower quality water from Long Pond. Additionally, sediment sampling and evaluation of nitrogen regeneration was conducted throughout the brackish water basins of Long Pond, which has very different circulation and tidal exchange characteristics than the more marine basins of the System. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density and spatial differences among the various basins and coves. For each core the nitrogen flux rates (described in the section above) were measured along with sediment organic carbon and nitrogen content, sediment type and an analysis of each site's tidal flow velocities. Bottom water flow velocity was relatively low throughout Long Pond and the upper portions of Hither Creek and low to moderate in the Madaket Harbor basin. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model for evaluating observed sediment characteristics. These data were then used to determine the nitrogen balance within each sub-embayment for parameterization of the water quality model.

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (Chapter V). 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 were 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.

The spatial pattern of sediment regeneration is consistent with the pattern of nitrogen entry into this estuary and the distribution of total nitrogen (TN) measured within the water column within those basins (Chapter VI). There was variability in the rates for each basin as samples were collected in patterns to purposely capture the spatial variation to adequately represent each sub-basin.

Rates of net nitrogen release or uptake from the sediments within the Madaket Harbor and Long Pond Embayment System were comparable to other embayments of similar depth in southeastern Massachusetts. There was a clear pattern of loss with the brackish water basins

of Long Pond and North Head of Long Pond with net release rates of 14 mg N L^{-1} and 6 mg N L^{-1}, respectively. The main basin of Madaket Harbor also showed a consistent low net release, averaging 6 mg N L^{-1}. In contrast, the relatively deep basin of Hither Creek operating as the major mixing basin for inflow from the Harbor and outflow from Long Pond via Madaket Ditch supported a small, but variable, net uptake of nitrogen -4 mg N L^{-1}. It is likely that the location and structure of Hither Creek and its depositional nature (likely enhanced by channel dredging) underlay the net uptake of nitrogen by this basin in summer. Hither Creek presently supports a marina that was constructed sometime after 1951 and to which a channel was dredged (1951 is the base year for the eelgrass trend assessment, Chapter VII). Deepening this basin alters the pattern of deposition and therefore likely has played a role in the present sediment distribution within this basin.

The observed sediment nitrogen regeneration rates reflect the functional components of the Madaket Harbor - Long Pond System. Madaket Harbor is an open-water well-flushed shallow basin. As such, it supports a low net nitrogen release (6 mg N L^{-1}). The sediments of this basin are generally composed of fine sands with silt and some areas of consolidated mud. The sediments consistently have an oxidized surface. Hither Creek is an artificially deepened basin that is depositional with typical sediments consisting very soft organic rich mud, with little oxidized surface layer and which supports a low net uptake of nitrogen (-4 mg N L^{-1}). These marine basins of the Estuary have rates of sediment nitrogen flux very similar to other similarly structured systems, like open water Ryders Cove and Bassing Harbor basins (12.3 - 19.7 mg N L-1) and the small depositional tributary of Frost Fish Creek (-5.1mg N L^{-1}). It is worth noting that basins most similar to the geomorphology and sediment characteristics of Madaket Harbor, also have nearly identical regeneration rates. For example, the large open water main basins of Phinneys Harbor, in Buzzards Bay, and Lewis Bay, in Nantucket Sound, have summer rates of 2.9 and 9.4 mg N L^{-1} for the outer and inner regions of Phinney's Harbor and 6.9 mg N L^{-1} for the Lewis Bay main basin, compared to 6 mg N L^{-1}, for Madaket Harbor.

The brackish water sub-basins of the Madaket Harbor - Long Pond System, Long Pond and North Head of Long Pond, support similar rates of net nitrogen release, 14 and 6 mg N L^{-1}, respectively. The similarity in rates reflects their similarity as brackish water wetland dominated basins that are shallow (<1 m) with sediments reflecting the low bottom water velocities and organic matter deposition. A similarly configured brackish basin, Mill Pond, in the Bassing harbor system, also showed similar rates, 12 mg N L^{-1}.

Overall, net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the Madaket Harbor - Long Pond Embayment System (Chapter VI) are presented in Table IV-4. Rates of sediment nitrogen regeneration throughout the Madaket Harbor - Long Pond System were low to moderate in magnitude, but comparable to similarly structured basins in southeastern Massachusetts. There was a clear spatial pattern of sediment nitrogen flux, with low rates of net release in the Harbor, low to moderate release rates in the brackish wetland basins, and a small net uptake in the depositional harbor basin of Hither Creek. The sediment nitrogen flux appears to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to the sub-basins.

Table IV-4. Rates of net nitrogen return from sediments to the overlying waters of the Madaket Harbor - Long Pond Embayment System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July -August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			Sta. i.d. *
	Mean	S.E.	# sites	
Madaket Harbor / Long Pond Embayment System **				
Madaket Harbor - Main Basin	**6**	**4**	**11**	**MAD: 1-8, 14-16**
Hither Creek	**- 4**	**14**	**5**	**MAD: 9-13**
North Head Long Pond	**6**	**6**	**2**	**LPN: 1,2**
Long Pond	**14**	**15**	**6**	**LPN: 3-8**

* Station numbers refer to Figures IV-9 and 10.
** Long Pond basins are brackish (8-15 ppt), Madaket Harbor and Hither Creek are marine (27-31 ppt).

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

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

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

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

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

The Madaket Harbor system (Figure V-1) is a tidally dominated embayment with a western opening to Nantucket Sound at the western extent of Nantucket Island. The Madaket Harbor system includes two sub-embayments, Hither Creek and Long Pond. Hither Creek is located east of Madaket Harbor and is connected to the harbor by a 150 foot wide channel. Further east is Long Pond, connected to Hither Creek by Madaket Ditch (a shallow, narrow ditch) with tidal exchange between the pond and creek occurring though a culvert under Madaket Road. Long Pond itself is divided into a northern and southern section by its orientation with Madaket Ditch. For the purposes of this analysis, Long Pond North is defined as the region of Long Pond north of the culvert under Madaket Road where it crosses Long Pond, and Long Pond South is defined as the region of Long Pond south of the Massasoit Bridge. The region in between is defined as Long Pond.

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

Since the water elevation difference between Nantucket Sound and Long Pond is the primary driving force for tidal exchange of this estuarine system, the local tide range limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) along the length of Madaket Harbor is negligible, indicating a system that flushes efficiently. Any issues with water quality, therefore, would likely be due to other factors including nutrient loading conditions from the system's watersheds, and the tide range in Nantucket Sound. Tidal damping between Madaket Harbor and Long Pond shows a significant reduction in amplitude indicating that issues with water quality would likely be strongly influenced by inadequate flushing.

Circulation in the Madaket Harbor estuarine system was simulated using the RMA-2 numerical hydrodynamic model. To calibrate the model, field measurements of water elevations and bathymetry were required. Tide data were acquired for the system at a gage station installed in Madaket Bay and at four stations located within the estuary (Figure V-2). All temperature-depth recorders (TDRs or tide gages) were installed for a 31-day period to measure tidal variations through one spring-neap tidal cycle. In this manner, attenuation of the tidal signal as it propagates through the harbor and Long Pond was evaluated accurately. Due to an error in data recording, the data from the Madaket Bay gage was corrupted, and was not used in this analysis, nor is the gage station shown in the figure. However, prior to the Madaket Bay gage becoming corrupted, the data was compared to the F Street gage and both the amplitude and phase were found to be identical. Therefore data from the F Street station was used as the offshore tidal signal for this analysis.

Figure V-2. Map of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. The four (4) gages were deployed for a 31-day period between May 8, and June 8, 2006. Each yellow dot represents the approximate locations of the tide gauges: (S-1) represents the F Street gage (Offshore), (S-2) the Long Pond gage, (S-3) the gage at the South Long Pond culvert, and (S-4) the gage inside the North Long Pond culvert.

V.2 FIELD DATA COLLECTION AND ANALYSIS

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

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

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

Boundary conditions for the numerical model consist of variations of water surface elevations measured in Nantucket 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 (gage locations are shown in Figure V-2). These measurements were used to calibrate and verify the model results, and to assure that the dynamic of the physical system were properly simulated.

V.2.1 Bathymetry

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

The first of two hydrographic surveys was conducted May 8th 2006 and collected bathymetry in Hither Creek. The second hydrographic survey, May 9-10th 2006, was designed to collect shallow water bathymetry in Madaket Ditch and Long Pond. Survey transects in both cases were densest in the vicinity of the inlets, were the greatest variability in bottom bathymetry was expected. Bathymetry in the inlet is important from the standpoint that it has the most influence on tidal circulation in and out of the estuary. The first survey was conducted from a shoal draft outboard boat with a precision fathometer installed (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide position measurements accurate to approximately 1-3 feet. Digital data output from both the echo sounder (fathometer) and GPS were logged to a laptop computer, which integrated the data to produce a single data set consisting of water depth as a function of geographic position (latitude/longitude). The second survey was conducted from a canoe with an installed precision fathometer (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide position measurements accurate to approximately 1-3 feet. Digital data output from both the echo sounder (fathometer) and GPS were logged into the GPS Data Logger. A digital output from the Data Logger produced a single data set consisting of water depth as a function of geographic position (latitude/longitude).

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to the North American Vertical Datum of 1988 (NAVD88) vertical datum in feet. Once rectified, the finished, processed data were archived as 'xyz' files containing x-y horizontal position (in Massachusetts Mainland State Plan 1983 coordinates) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The final processed bathymetric data from the survey are presented in Figure V-3.

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

V.2.2 Tide Data Collection and Analysis

Variations in water surface elevation were measured at stations in four locations in the Madaket Harbor estuary and at a station in Madaket Bay. The station location in Madaket Bay is located just offshore on the north side of Esther Island (S-1), and due to an error in data recording, the data from this gage was corrupted. Stations within the Madaket Harbor estuary system were located in Hither Creek on the southeast bank (S-2), south of the bridge on Madaket Road near Long Pond North (S-3), north of the bridge on Madaket Road in Long Pond North (S-4), and south of the Massasoit Bridge on the south side of Long Pond (S-5). TDRs were deployed at each gage station from the beginning of May 8th through June 8th 2006. The duration of the TDR deployment allowed time to conduct the bathymetric surveys, as well as sufficient data to perform a thorough analysis of the tides in the system.

The tide records from Madaket Harbor were corrected for atmospheric pressure variations and then rectified to the NAVD88 vertical datum. Atmospheric pressure data, available in one-hour intervals from the NDBC Buzzards Bay C-MAN platform, were used to pressure correct the raw tide data. Final processed tide data from the stations used for this study are presented in Figure V-4, for the complete 31-day period of the TDR deployment.

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

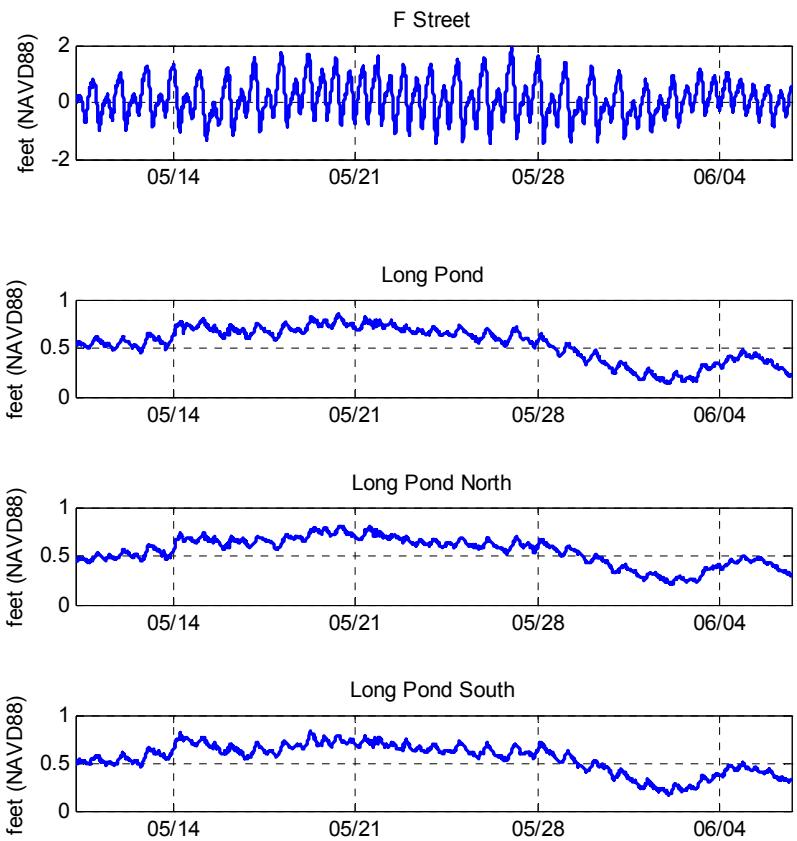

Figure V-4. Water elevation variations as measured at the four locations of the Madaket Harbor system, from May 09th to June 07th 2006.

The loss of amplitude together with increasing phase delay with increasing distance from the inlet is described as tidal attenuation. Tide attenuation can be a useful indicator of flushing efficiency in an estuary. Attenuation of the tidal signal is caused by the geomorphology of the near-shore region, where channel restrictions (e.g., bridge abutments) and also the depth of an estuary are the primary factors which influence tidal damping in estuaries. A visual comparison of the four stations throughout the Madaket Harbor estuary system (Figure V-5), demonstrates clearly a reduction in the tidal efficacy of Long Pond.

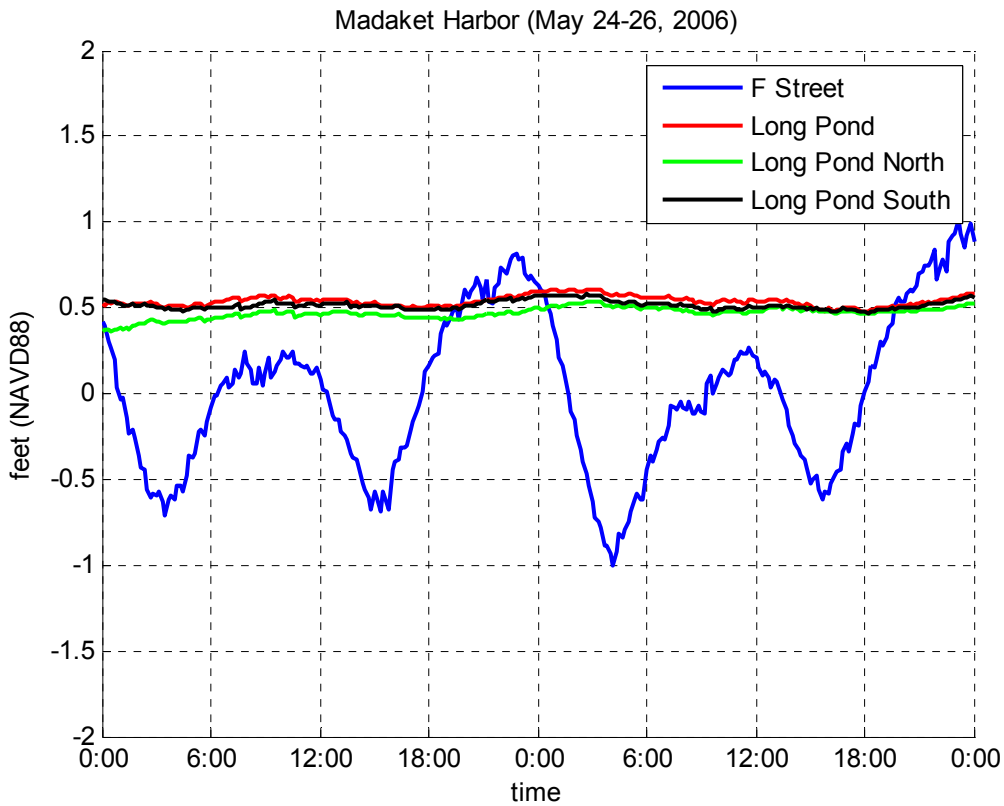

Figure V-5. Plot showing two tide cycles tides at four stations in the Madaket Harbor system plotted together. Demonstrated in this plot is the amplitude reduction and mean water level increase in Long Pond caused by the propagation of the tide through the culvert in Madaket Ditch under Madaket Road.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 31-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 Nantucket 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 is further apparent that there is significant damping occurring between Long Pond and Hither Creek, but almost no damping inside Long Pond.

Table V-1. Tide datums computed from records collected in the Madaket Harbor Estuarine system May 10 - June 06, 2006. Datum elevations are given relative to NAVD88

Tide Datum	F Street	Long Pond North	Long Pond	Long Pond South
Maximum Tide	1.916	0.814	0.854	0.829
MHHW	1.297	0.622	0.635	0.642
MHW	0.903	0.589	0.590	0.597
MTL	0.024	0.549	0.543	0.553
MLW	-0.855	0.509	0.495	0.508
MLLW	-1.072	0.489	0.479	0.491
Minimum Tide	-1.474	0.211	0.138	0.172

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

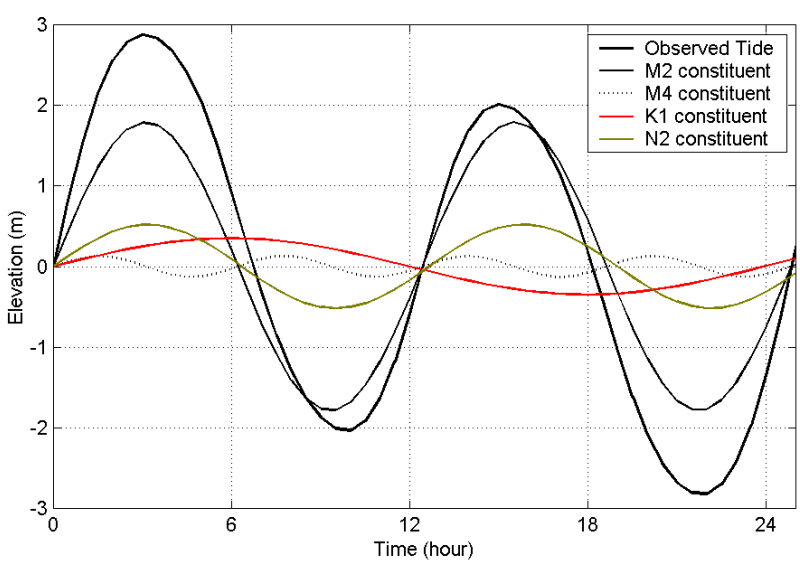

Figure V-6. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-2 presents the amplitudes of seven significant tidal constituents. The M_2, or the familiar twice-a-day lunar, semi-diurnal, tide is the strongest contributor to the signal outside Madaket Ditch, while the MSF, the lunisolar synodic, fortnightly constituent, is the largest constituent inside Long Pond. The MSF inside Long Pond is roughly half the amplitude as it is in Hither Creek, where the M2 amplitude drops by a factor of 30 going through Madaket Ditch, demonstrating the near-isolation Long Pond has from Hither Creek. The range of the M_2 tide is twice the amplitude, or about 1.40 feet in Hither Creek and 0.42-0.56 feet in Long Pond. The diurnal (once daily) tide constituents, K_1 (solar), O_1 (lunar), and 2Q1 (larger elliptic diurnal) possess amplitudes of approximately 0.03-0.06 feet, 0.07 feet, and 0.02 feet respectively in Long Pond and 0.63 feet, 0.56 feet and 0.02 feet respectively in Hither Creek. These constituents account for the semi-diurnal variance one high/low tide to the next, as seen in figure V-5. The M_4 tide, a higher frequency harmonic of the M_2 lunar tide (twice the frequency of the M_2), results from frictional dissipation of the M_2 tide in shallow water.

Table V-2. Tidal Constituents for the Madaket Harbor System. Data collected May 10 - June 6, 2006.

AMPLITUDE (feet)							
	M2	M4	M6	K1	2Q1	MSF	O1
Period (hours)	12.42	6.21	4.14	23.93	28.00	354.61	25.82
F Street	0.695	0.192	0.021	0.317	0.011	0.115	0.281
Long Pond North	0.021	0.000	0.001	0.015	0.009	0.043	0.034
Long Pond	0.027	0.002	0.002	0.029	0.011	0.072	0.034
Long Pond South	0.028	0.002	0.002	0.026	0.011	0.060	0.031

Table V-3 presents the phase delay (in other words, the travel time required for the tidal wave to propagate throughout the system) of the M_2 tide at all tide gauge locations inside the system. The greatest delay occurs between the F Street gage station and Long Pond North gage stations. The largest changes in phase delay occur between the Long Pond gage station and Long Pond North. This suggests some amount of hydraulic inefficiency being caused by the culvert in Madaket Road that separates the Long Pond and Long Pond North gage stations. The long delays from F Street to Long Pond are expected given the signal must travel through Madaket Ditch

Table V-3. M2 Tidal Attenuation, Madaket Harbor Estuary System, May 10 - June 6, 2006 (Delay in minutes relative to F Street).

Location	Delay (minutes)
Long Pond North	245
Long Pond	177
Long Pond South	185

The tide data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. Non-tidal processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow. The results of an analysis to determine the energy distribution (or variance) of the original water elevation time series for the two river systems is presented in Table V-4 compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 23 constituents determined by the harmonic analysis). Subtracting the tidal signal from the original elevation

time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes are relative to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from F Street, with the predicted tide resulting from the harmonic analysis, and the resulting non-tidal residual.

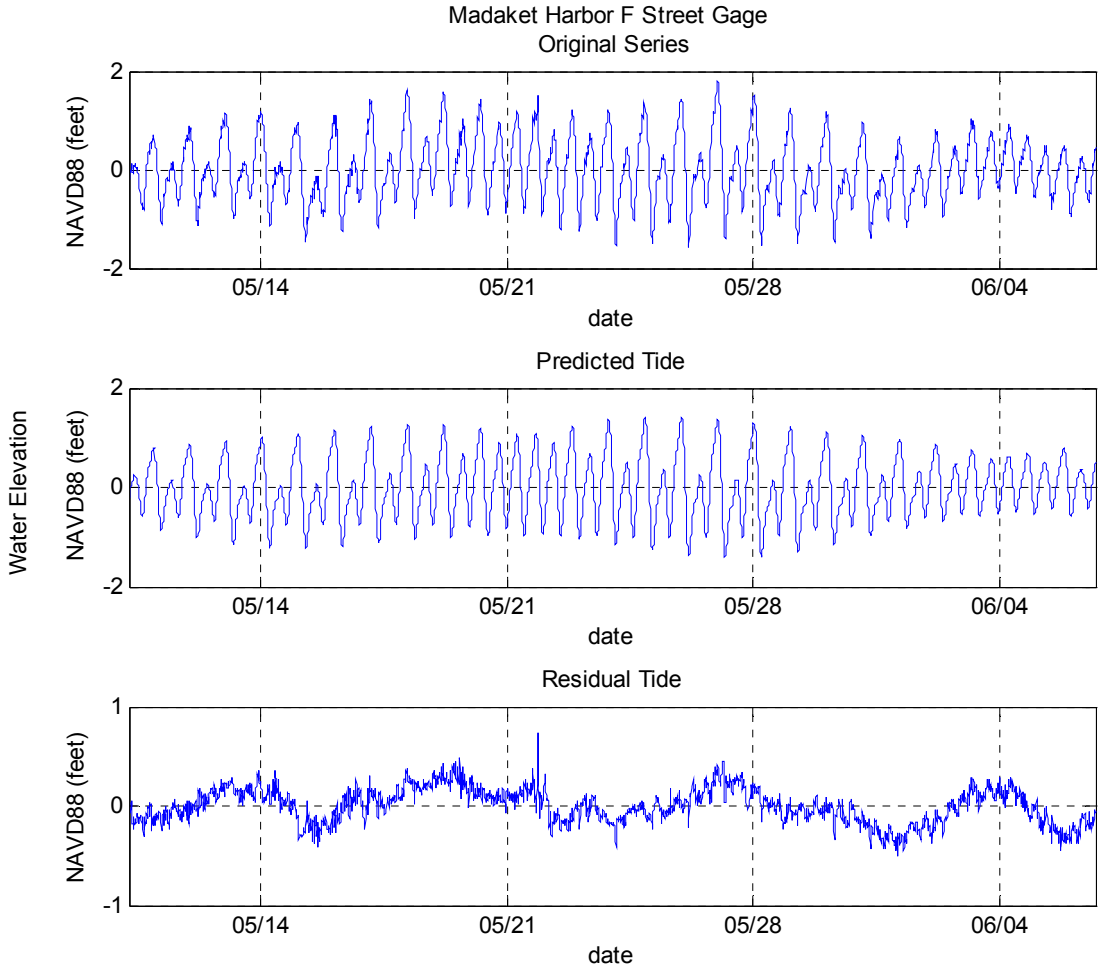

Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured at the F Street Gage (S-1).

Table V-4 shows that the percentage contribution of tidal energy was the predominate driving force of the observed tidal signal in Hither Creek, while the residual signal was the driving force inside of Long Pond. The analysis also shows that tides are responsible for 92% of the water level changes in Hither Creek and Madaket Bay, while the tides are only responsible for 9% to 13% of the water level changes inside of Long Pond. The remaining 8% for Hither Creek and Madaket Bay was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of Nantucket Sound, Madaket Bay, and Hither Creek. The remaining 87% to 91% of the water level changes inside of Long Pond is likely due to the constriction of the system through the Madaket Ditch Culvert located under Madaket Road. The total energy content of the tide signal should carry over from one embayment to the next unless tidal flow is inhibited. This can be seen clearly in the reduction of

the total variance by an order of magnitude from Hither Creek to Long Pond, and by the increased percent of non-tidal factors influencing the tidal signal in Long Pond.

Table V-4. Percentages of Tidal versus Non-Tidal Energy, Hither Creek and Long Pond, 2006

Location	Total Variance (ft^2)	Total (%)	Tidal (%)	Non-tidal (%)
F Street	0.409	100	92.91	7.09
Long Pond	0.032	100	12.50	87.50
Long Pond North	0.021	100	9.52	90.48
Long Pond South	0.023	100	13.04	86.96

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

V.3 HYDRODYNAMIC MODELING

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

V.3.1 Model Theory

This study of Madaket Harbor utilized a state-of-the-art computer model to evaluate tidal circulation and flushing. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2 for numerous flushing studies for estuary systems in southeast Massachusetts, including systems in Chatham, Falmouth's 'finger' ponds, and Popponesset Bay.

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). SMS is a front- and back-end software package that allows the user to easily modify model parameters (such as geometry, element coefficients, and boundary conditions), as well as view the model results and download specific

data types. While the RMA model is essentially used without cost or constraint, the SMS software package requires site licensing for use.

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

The extent of the finite element grid was generated using digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of the system based on the tide gauge data collected at the F Street gage location. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several (15+) 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 2179 elements and 6372 nodes (Figure V-8). All regions in the system were represented by two-dimensional (depth-averaged) elements. The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties within the estuary. Fine resolution was required to simulate the numerous channel constrictions (e.g., at the culverts in Madaket Ditch) that significantly impact the estuarine hydrodynamics. The completed grid is made up of quadrilateral and triangular two-dimensional elements. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the recent field surveys and the NOAA data archive. The final interpolated grid bathymetry is shown in Figure V-9. The model computed water elevation and velocity at each node in the model domain.

Grid resolution is governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each region. Smaller cross channel node spacing in the river channels was designed to provide a more detailed analysis in these regions of rapidly varying velocities

and bathymetry. Widely spaced nodes were utilized in areas where velocity gradients were likely to be less acute; for example, in broad, deep channel sections in the model domain. Appropriate implementation of wider node spacing and larger elements reduces computer run time with no sacrifice of accuracy.

V.3.2.2 Boundary Condition Specification

Two types of boundary conditions were employed for the RMA-2 model: 1) "slip" boundaries and 2) tidal elevation boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations.

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

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

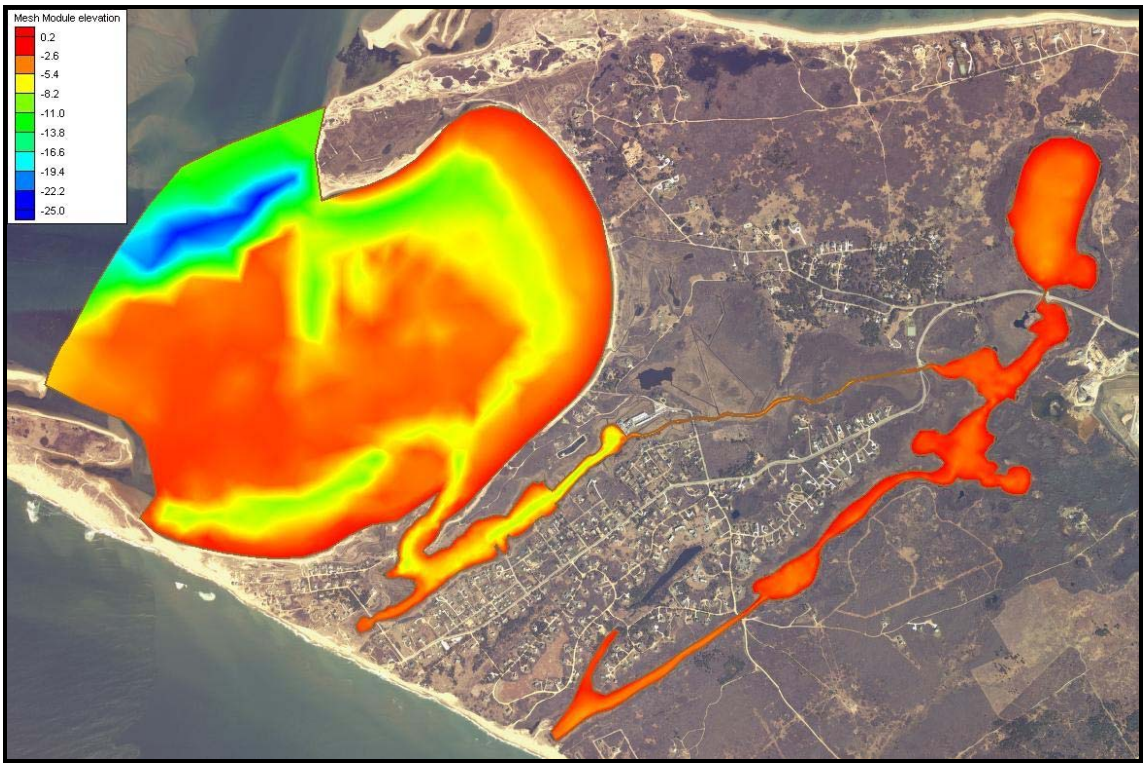

Figure V-9. Depth contours of the completed Madaket Harbor finite element mesh.

V.3.3 Calibration

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

Calibration of the flushing model required a close match between the modeled and measured tides at each gage station. Initially, the model was calibrated by the visual agreement between modeled and measured tides. To refine the calibration procedure, water elevations were output from the model at the same locations in the estuary where tide gauges were installed, and the data were processed to calculate standard error as well harmonic constituents (of both measured and modeled data) over the thirteen-day calibration period. The amplitude and phase of four constituents (M_2, M_4, O_1, and K_1) were compared and the corresponding errors for each were calculated. The intent of the calibration procedure is to minimize the error in amplitude and phase of the individual constituents. In general, minimization of the M_2 amplitude and phase becomes the highest priority, since this is the dominant constituent. Emphasis is also placed on the M_4 constituent, as this constituent has the greatest impact on the degree of tidal distortion within the system, and provides the unique shape of the modified tide wave at various points in the system.

The calibration was performed for an approximate thirteen-day period, beginning 2020 hours EDT May 22, 2006 and ending 2010 hours EDT June 4, 2006. This time period included a 48-hour model spin-up period, and a 20-tide cycle period used for calibration. This

representative time period was selected because it included tidal conditions where the wind-induced portion of the signals (i.e. the residual) was minimal, hence more typical of tidal circulation within the estuary. The selected time period also spanned the transition from spring (bi-monthly maximum) to neap (bi-monthly minimum) tide ranges, which is representative of average tidal conditions in the embayment system. Throughout the selected 11 day period after the spin-up, the tide ranged approximately 3.4 feet from minimum low to maximum high tides. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. Modeled tides were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.3.3.1 Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where water depths can become shallow and velocities relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude attenuation and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient. First, Manning's friction coefficient values of 0.025 were specified for all elements. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels with pools and shoals with higher friction (Henderson, 1966). Final calibrated friction coefficients (listed in Table V-5) were largest for Madaket Ditch Culvert under Madaket Road, where values were set at 0.1. This setting was used to approximate a culvert that is completely submerged for portions of the tidal cycle, to properly damp the tidal signal in Long Pond to correspond with measured values (see V.2.2.2). Small changes in these values did not change the accuracy of the calibration.

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

Embayment	Bottom Friction
Culvert	0.040
Madaket Ditch	0.040
Long Pond North	0.015
Long Pond South	0.025
Hither Creek	0.025
Madaket Harbor	0.015
Mouth of Harbor	0.020
Madaket Ditch Culvert	0.100
Long Pond	0.025

V.3.3.2 Turbulent Exchange Coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swift, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). The model was mildly sensitive to turbulent exchange coefficients, with Madaket Bay and Hither Creek being most sensitive. In other regions where the flow gradients were not as strong, the model was much less sensitive to changes in the turbulent exchange coefficients. Typically, model turbulence coefficients (D) are set between 10 and 100 lb-sec/ft^2 (as listed in Table V-6).

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

Embayment	D (lb-sec/ft$^{2)}$
Culvert	40
Madaket Ditch	25
Long Pond North	20
Long Pond South	20
Hither Creek	100
Madaket Harbor	100
Mouth of Harbor	100
Madaket Ditch Culvert	100
Long Pond	20

V.3.3.3 Wetting and Drying/Marsh Porosity Processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain included in the model as part of Madaket Ditch in the Madaket Harbor system. Cyclically wet/dry areas of the marsh will tend to store waters as the tide begins to ebb and then slowly release water as the water level drops within the creeks and channels. This store-and-release characteristic of these marsh regions was partially responsible for the distortion of the tidal signal, and the elongation of the ebb phase of the tide. On the flood phase, water rises within the channels and creeks initially until water surface elevation reaches the marsh plain, when at this point the water level remains nearly constant as water 'fans' out over the marsh surface. The rapid flooding of the marsh surface corresponds to a flattening out of the tide curve approaching high water. Marsh porosity is a feature of the RMA-2 model that permits the modeling of hydrodynamics in marshes. This model feature essentially simulates the store-and-release capability of the marsh plain by allowing grid elements to transition gradually between wet and dry states. This technique allows RMA-2 to change the ability of an element to hold water, like squeezing a sponge. 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.3.3.4 Comparison of Modeled Tides and Measured Tide Data

Several calibration model runs were performed to determine how changes to various parameters (e.g. friction and turbulent exchange coefficients) affected the model results. These trial runs achieved excellent agreement between the model simulations and the field data. Comparison plots of modeled versus measured water levels at the four gauge locations are presented in Figures V-10 through V-13. At all gage stations, RMS errors were less than 0.07 ft (<0.85 inches) and computed R^2 correlation was better than 0.93 for every station except the Long Pond station, which had a computed R^2 correlation of 0.747. Errors between the model and observed tide constituents were less than 0.03 feet for all locations, suggesting the model accurately predicts tidal hydrodynamics within Madaket Harbor. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the calibration time period are shown in Table V-7. The constituent values in for the calibration time period differ from those in Table V-2 because constituents were computed for only 11 days, rather than the entire 31-day period represented in Table V-2. Errors associated with tidal constituent height were on the order of hundredths of feet, which was an order of magnitude better than the accuracy of the tide gage gauges (±0.12 ft). Time lag errors were close to the time increment resolved by the model and measured tide data (1/6 hours or 10 minutes) for the F Street gage, indicating good agreement between the

model and data. The larger lag values for Long Pond are expected with such a large portion of the water elevation change due to residual energy (see table V-4).

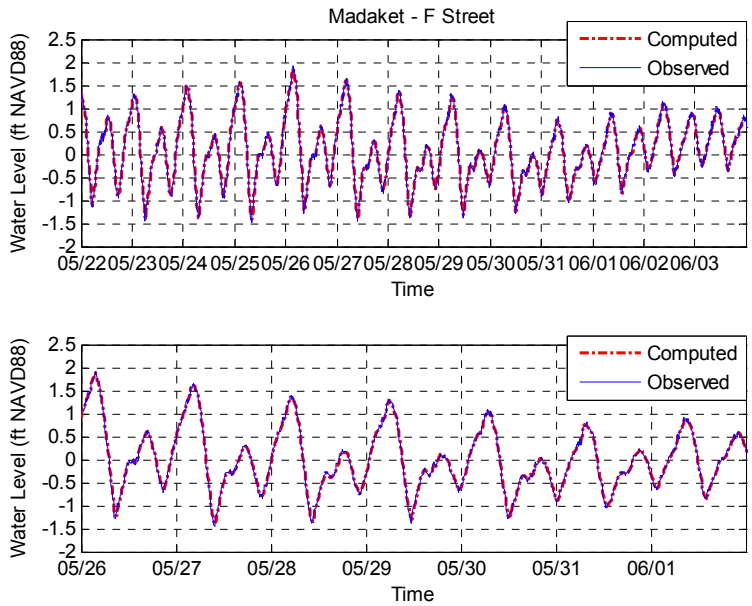

Figure V-10. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the F Street Gage Station. The top plot shows the entire record with the bottom plot showing an 8-day segment.

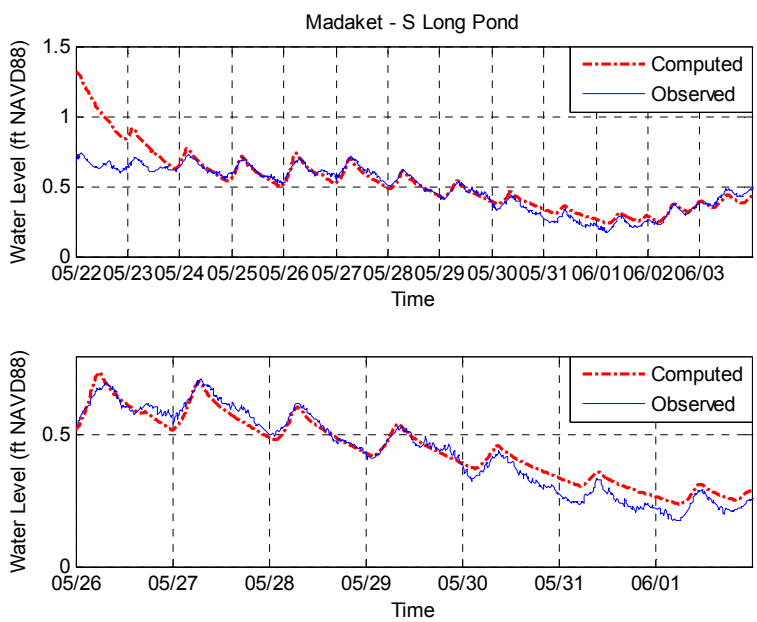

Figure V-11. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Long Pond South Gage Station. The top plot shows the entire record with the bottom plot showing an 8-day segment.

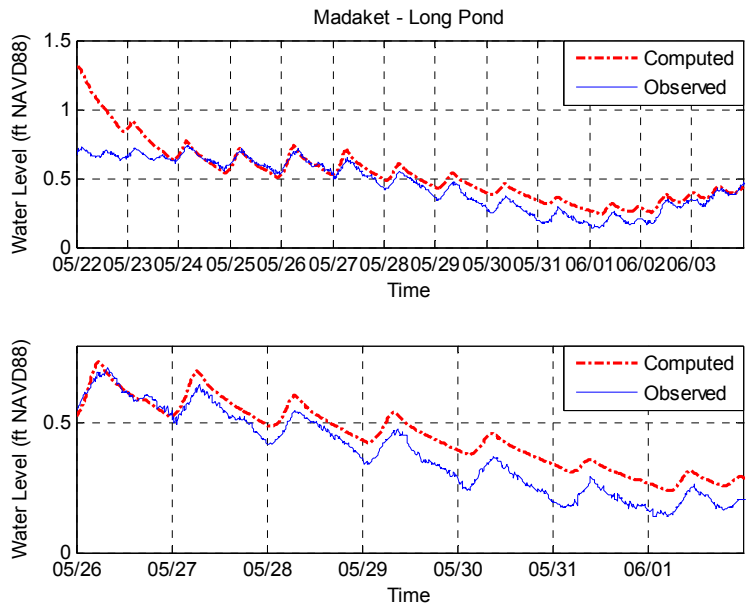

Figure V-12. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Long Pond Gage Station. The top plot shows the entire record with the bottom plot showing an 8-day segment.

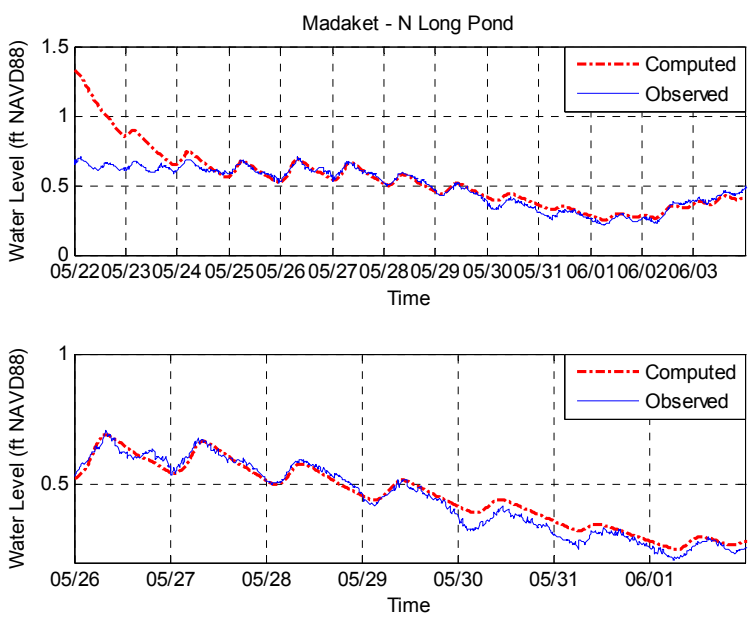

Figure V-13. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Long Pond North Gage Station. The top plot shows the entire record with the bottom plot showing an 8-day segment.

Table V-7. Comparison of Tidal Constituents calibrated RMA2 model versus measured tidal data for the period May 24 to June 4, 2006.						
Model Verification Run						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	O_1	K_1	ΦM_2	ΦM_4
F Street	0.698	0.203	0.303	0.333	-177.0	126.8
Long Pond North	0.016	0.001	0.031	0.027	-49.2	-138.9
Long Pond	0.026	0.004	0.035	0.034	-99.9	115.7
Long Pond South	0.027	0.004	0.036	0.034	-94.5	131.7
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	O_1	K_1	ΦM_2	ΦM_4
F Street	0.700	0.219	0.322	0.310	-177.8	122.7
Long Pond North	0.018	0.002	0.032	0.014	-56.6	-53.3
Long Pond	0.026	0.001	0.034	0.027	-94.4	142.7
Long Pond South	0.027	0.002	0.031	0.024	-90.4	-175.0
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	O_1	K_1	ΦM_2	ΦM_4
F Street	0.002	0.016	0.019	-0.023	-1.7	-4.3
Long Pond North	0.002	0.001	0.000	-0.013	-15.4	88.6
Long Pond	0.000	-0.003	-0.001	-0.007	11.4	27.9
Long Pond South	0.000	-0.003	-0.005	-0.010	8.5	-317.5

V.3.4 Model Circulation Characteristics

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

From the model run of the estuary system, maximum flood velocities at the Hither Creek inlet are slightly smaller than velocities during the ebb portion of the tide. Maximum depth-averaged velocities in the model are approximately 0.3 feet/sec for flooding tides, and 0.55 ft/sec for ebbing tides. A close-up of the model output is presented in Figure V-14, which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow, for a single model time-step, at the portion of the tide where maximum flood velocities occur at the inlet.

In addition to depth averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs through the Madaket Harbor Estuarine system is seen in Figure V-15. During the simulation time period, maximum modeled flood tide flow rates through the Hither Creek inlet were 321 ft^3/sec and ebb tide flow rates were 449 ft^3/sec. The lack of a second flood and ebb cycle inside Long Pond is due to the increased elevation of the pond. The maximum modeled flood tide flow rates through the Madaket Ditch culvert (near Long Pond) were 61 ft^3/sec and ebb tide flow rates were 35 ft^3/sec, and the flood tide flow rates for the Long Pond North culvert were 20 ft^3/sec and the ebb tide flow rates were 15 ft^3/sec.

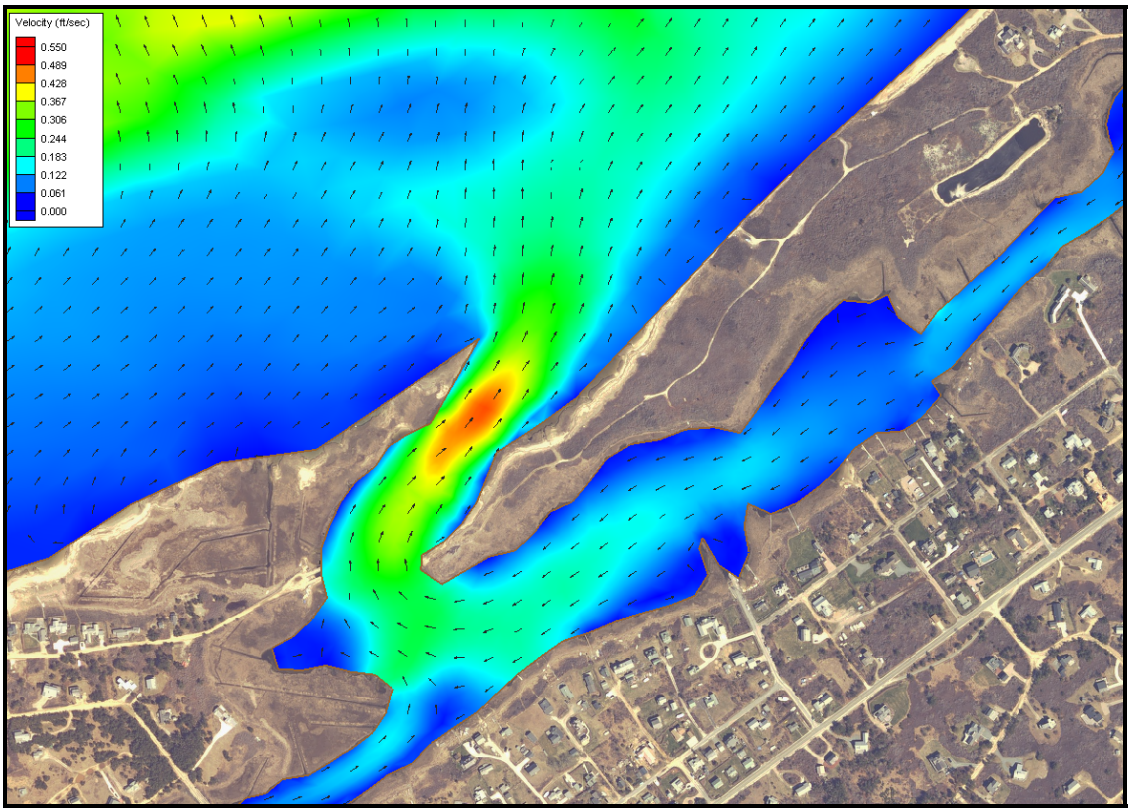

Figure V-14. Example of hydrodynamic model output in Hither Creek for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

V.4 FLUSHING CHARACTERISTICS

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

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

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

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

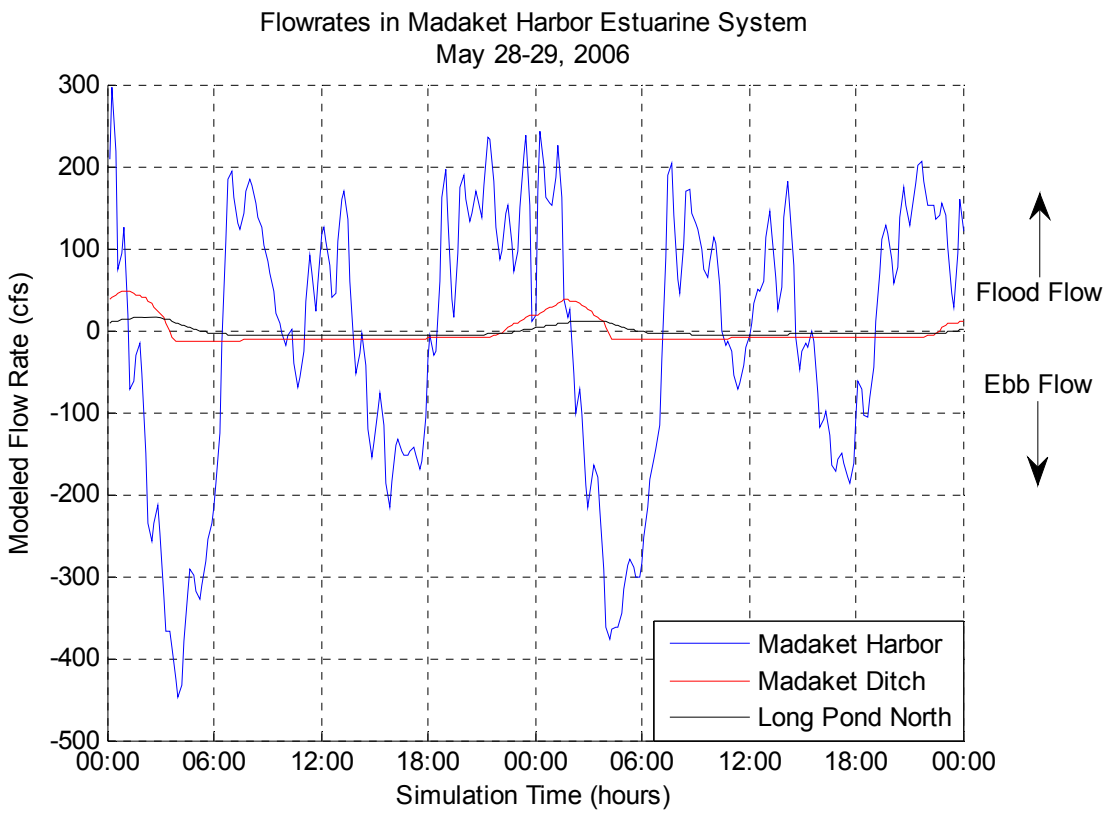

Figure V-15. Time variation of computed flow rates for transects across Hither Creek inlet, the Madaket Ditch culvert near Long Pond, and the entrance to Long Pond North. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are likewise large compared to neap tide conditions. Positive flow indicates flooding tide, while negative flow indicates ebbing tide.

In addition to system residence times, a second residence, the local residence time, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using the head of Madaket Harbor as an example, the system residence time is the average time required for water to migrate from the head of Madaket Harbor, through the lower portions of the Harbor, and finally into Nantucket Sound, where the local residence time is the average time required for water to migrate from the head of the Harbor to just the mid portion of the Harbor (not all the way to the inlet and out of the system). Local residence times for each sub-embayment are computed as:

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

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

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

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

The volume of each sub-embayment, as well as their respective tidal prisms, was computed in cubic feet (Table V-8). Model divisions used to define the system sub-embayments for the two systems include 1) the whole of the Madaket Harbor system, 2) Hither Creek, 3) Long Pond, 4) Long Pond South, and 5) the section of Long Pond North labeled North Head Long Pond (Figure V-1). The model computed total volume of each sub-embayment at every time step, and this output was used to calculate mean sub-embayment volume and average tide prism. Since the 10-day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

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

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Madaket Harbor	186,012,000	59,488,000
Hither Creek	16,604,000	2,829,000
Long Pond – All	9,822,000	328,000
Long Pond South	1,385,000	49,000
Long Pond North	4,333,000	107,000

Residence times were averaged for the tidal cycles comprising a representative 10 day period (19 tide cycles), and are listed in Table V-9. Residence times were computed for the entire estuary, as well selected sub-embayments within the two systems. In addition, system and local residence times were computed to indicate the range of conditions possible for the system. Residence times were calculated as the volume of water (based on mean volumes computed for the simulation period) in the entire system divided by the average volume of water

exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days.

The moderate local residence time (1.6 days) of the whole Madaket Harbor estuary system shows that the outer harbor area most likely flushes reasonably well. However, with the rapid increase in the local residence times (from twice as long to almost 14 times as long) of the embayments as water progresses deeper into the system, it should be assumed that the flushing of the system as a whole is poor at best. The extreme lengths of the system residence times inside Long Pond (from almost a year for the entirety of the pond to 2.5-6 years for the deeper embayments), as well as a progressive decline in salinity in Long Pond to roughly 1/3 of the salinity of the bay confirm the poor flushing of the system.

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

Embayment	Local Residence Time (days)	System Residence Time (days)
Madaket Harbor	1.6	1.6
Hither Creek	3.1	34.2
Long Pond – All	15.6	295
Long Pond South	14.6	1960
Long Pond North	21.0	901

Based on our knowledge of estuarine processes, we estimate that the combined errors associated with the method applied to compute residence times are within 10% to 15% of “true” residence times, for the Madaket Harbor estuary system. Possible errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. In this study, the most significant errors associated with the bathymetry data result from the process of interpolating the data to the finite element mesh, which was the basis for all the flushing volumes used in the analysis. In addition, limited topographic measurements were available in some of the smaller sub-embayments of the system.

Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. However, water exiting a small sub-embayment on a relatively calm day may not completely mix with estuarine waters. In this case, the “strong littoral drift” assumption would lead to an under-prediction of residence time. Since littoral drift in Nantucket Sound is typically strong because of the effects of the local winds and tidal induced mixing, the “strong littoral drift” assumption should cause only minor errors in residence time calculations.

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort for the Madaket Harbor System. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayment

Extensive field measurements and hydrodynamic modeling of the embayment were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated model output representing the transport of water within the system embayment. Files of node locations and node connectivity for the RMA-2V model grid were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic output for the water quality model calibration was a 37-tidal cycle period in May 2006. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 38-day spin-up period, to allow the model to reach a dynamic “steady state”, and ensure that model spin-up would not affect the final model output. This relatively long spin-up period was required, due to the inefficient tidal exchange between Hither Creek and Long Pond.

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 Madaket Harbor 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. 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. Three years of data (collected between 2002 and 2004) were available for stations monitored by SMAST in the Madaket Harbor System. The data was examined for temporal trends, as well as consistency between laboratories and sampling groups prior to use. While it may appear from the averages presented in Table VI-1 that in some instances there may be some temporal trend in TN levels, temporal analysis on averages masks the variability of the annual data. From more detailed analysis it appears that the different groups/laboratories conducting the monitoring had different associated ranges of variation in the subsequent resulting annual data (i.e. different years had very different annual variations). However, individual station analysis indicated that the regressions of individual TN samples versus time had little real temporal trend ($R2<0.25$). For example, examination of

station M11, in Hither Creek, found that the regression over time only accounted for 22% of the trend line. More importantly, there were no significant differences between years and the data range varied almost 4 fold between years. A similar result was found by the Cadmus Group in their analysis of Pleasant Bay water quality data for the Pleasant Bay Alliance (2010). Given the lack of interannual differences, it is appropriate in the present study (as in the Cadmus Study) to use the overall average of the multiyear water quality dataset as the typical condition within the Madaket/Long Pond Estuary (Table VI-1). **This appropriateness of the 2002-2004 baseline TN levels was confirmed by more recent data collected by the Nantucket Water Quality Monitoring Program summer 2010 that shows a mean TN level at station M11 of 0.626 mg TN/L compared to the 0.620 mean from 2002-2004 for this key station in Hither Creek used in the MEP water quality analysis.**

VI.2 MODEL DESCRIPTION AND APPLICATION

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of nitrogen loading in the Madaket Harbor System. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate

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

Sub-Embayment	Monitoring station	2002 mean	2003 mean	2004 mean	mean	s.d. all data	N	model min	model max	model average
Madaket Harbor	M1	0.402	0.333	0.272	0.336	0.098	25	0.3053	0.3197	0.3107
Madaket Harbor	M2	0.427	0.413	0.349	0.395	0.083	27	0.3165	0.324	0.3205
Madaket Harbor	M3	0.501	0.387	0.347	0.415	0.090	27	0.3186	0.3411	0.328
Hither Creek	M4	0.644	0.647	0.422	0.581	0.193	35	0.3986	0.5423	0.4639
Hither Creek	M5	0.883	0.691	0.684	0.780	0.178	19	0.4946	0.6945	0.613
Madaket Harbor	M6	0.419	0.317	0.315	0.347	0.067	10	0.3095	0.3279	0.3161
Madaket Harbor	M10	0.527	0.431	0.312	0.422	0.127	16	0.3192	0.3424	0.3266
Hither Creek	M11	0.690	0.636	0.441	0.620	0.215	24	0.4587	0.5732	0.5107
Long Pond	LOPO1	1.243	0.746	1.185	1.058	0.404	18	0.9997	1.1027	1.0394
Long Pond	LOPO2	1.157	0.860	0.895	0.971	0.369	18	0.9336	1.0513	0.9827
Long Pond	LOPO3	--	1.001	0.848	0.924	0.234	10	0.818	0.956	0.8821
Long Pond	LOPO4	0.939	0.889	0.821	0.894	0.278	25	0.7542	0.9319	0.8515
North Head Long Pond	LOPO5	1.029	0.929	0.781	0.954	0.271	26	0.8674	0.9345	0.8937

the fluid dynamics of the Madaket Harbor System. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod embayments, including systems in Falmouth (Ramsey *et al*., 2000); Mashpee, MA (Howes *et al*., 2004) and Chatham, MA (Howes *et al*., 2003).

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

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

VI.2.1 Model Formulation

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

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

where c is 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 Madaket Harbor System.

VI.2.2 Water Quality Model Setup

Required inputs to the RMA-4 model include a computational mesh, computed water elevations and velocities at all nodes of the mesh, constituent mass loading, and spatially varying values of the dispersion coefficient. Because the RMA-4 model is part of a suite of integrated computer models, the finite-element meshes and the resulting hydrodynamic simulations previously developed for the Madaket Harbor System was used for the water quality constituent modeling portion of this study. Based on groundwater recharge rates from the USGS the overall groundwater flow rate into the system is 8.71 ft^3/sec (21,325 m^3/day) distributed amongst the watersheds.

For the model, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated spin-up period of just over a month (38 days). At the end of the spin-up period, the model was run for an additional 37 tidal-cycle (460 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the Madaket Harbor System.

VI.2.3 Boundary Condition Specification

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

The loadings used to model present conditions in Madaket Harbor System are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment, resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For present conditions, some sub-embayments have almost twice the loading rate from benthic regeneration as from watershed loads. For other sub-embayments, the benthic flux is relatively low or negative indicating a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in Nantucket Sound was set at 0.30 mg/L, based on SMAST data from the 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 VI-2. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent areas of Madaket Harbor require values of *E* that are lower compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979). Observed values of *E* in these calmer areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of *E* used in each sub-embayment of the modeled systems are presented in Table VI-3. These values were used to develop the “best-fit” total nitrogen model calibration. For the case of TN modeling, “best fit” can be defined as minimizing the error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Madaket Harbor	0.663	8.603	17.952
Hither Creek	4.041	0.534	-0.583
Madaket Ditch	2.433	-	0.061
Long Pond	3.230	0.975	3.065
North Head Long Pond	0.238	0.693	0.995

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

Embayment Division	E m^2/sec
Madaket Harbor	10.0
Hither Creek (Mouth)	5.0
Hither Creek (Upper)	2.5
Hither Creek (Middle)	25.0
Hither Creek (Lower)	25.0
Madaket Ditch (West Culvert)	75.0
Madaket Ditch	75.0
Madaket Ditch (East Culvert)	100.0
Long Pond	20.0
North Head Long Pond	10.0
Long Pond (South Culvert)	0.5

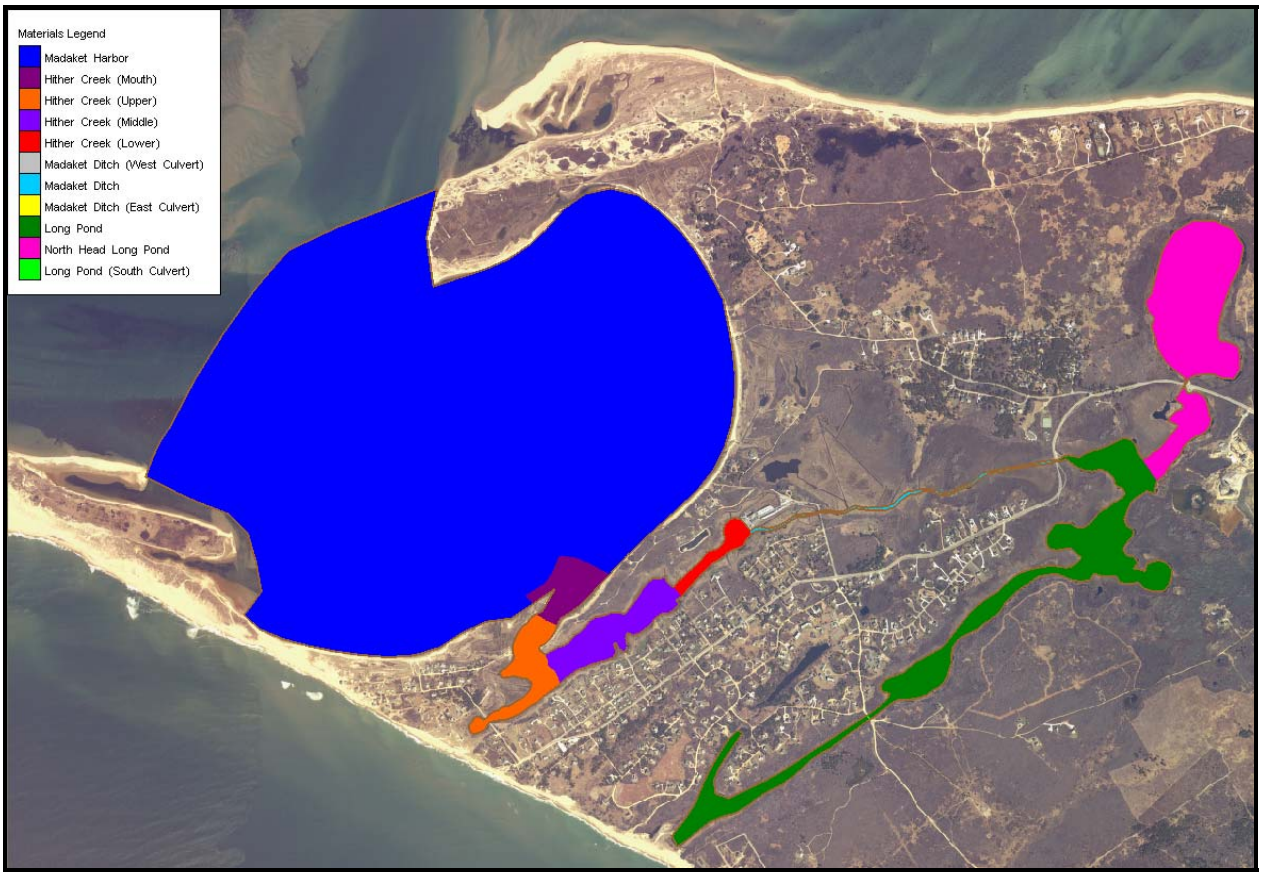

Figure VI-2. Map of Madaket Harbor water quality model longitudinal dispersion coefficients. Color patterns designate the different areas used to vary model dispersion coefficient values.

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

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

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for the system. The model fit is exceptional for the Madaket Harbor System, with rms error of 0.081 mg/L and an R^2 correlation coefficient of 0.90.

A contour plot of calibrated model output is shown in Figure VI-4 for Madaket Harbor System. In the figure, color contours indicate nitrogen concentrations throughout the model domain. The output in the figure show average total nitrogen concentrations, computed using the full 19-tidal-day model simulation output period.

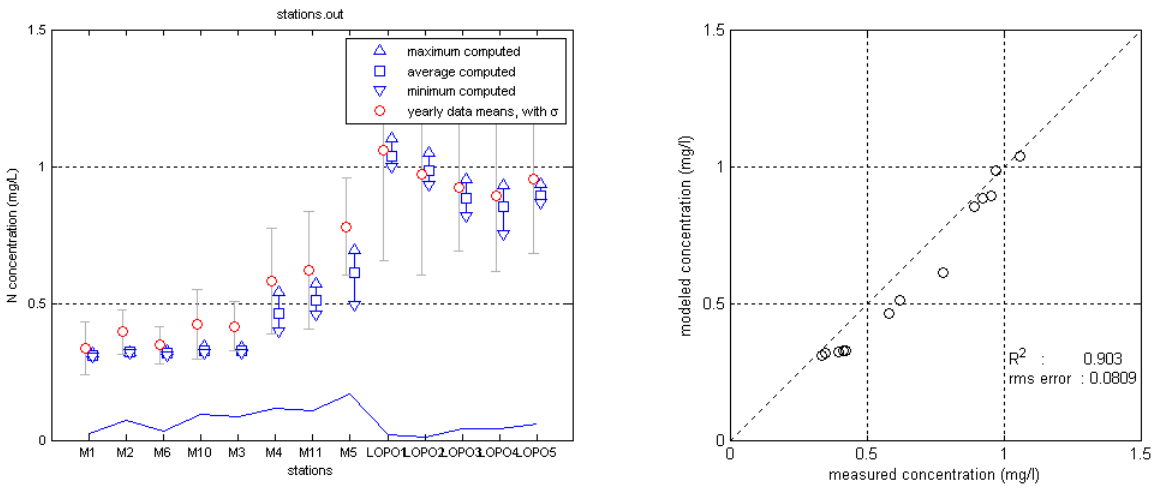

Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Madaket Harbor System. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

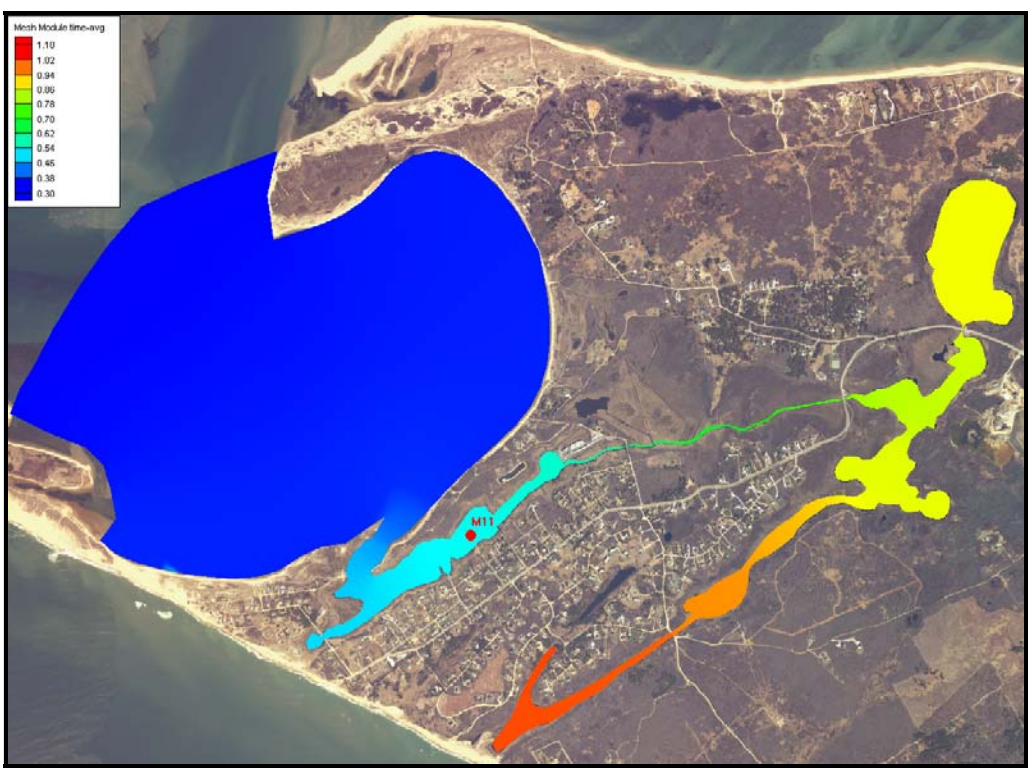

Figure VI-4. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for Madaket Harbor System. The approximate location of the sentinel threshold station for Madaket Harbor System (M11) is shown.

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 Madaket Harbor System using salinity data collected at the same stations as the nitrogen data. The only required inputs into the RMA4 salinity model of each system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, and groundwater inputs. The open boundary salinity was set at 31.7 ppt. For groundwater inputs, salinities were set at 0 ppt. Groundwater input used for the model was 8.71 ft^3/sec (21,325 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed evenly in each model through the use of several rainwater element input points positioned along each model's land boundary.

Comparisons of modeled and measured salinities are presented in Figure VI-5, with contour plots of model output shown in Figure VI-6. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in Madaket Harbor System. The rms error of the models was 2.695 ppt, and correlation coefficient was 0.92. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical systems.

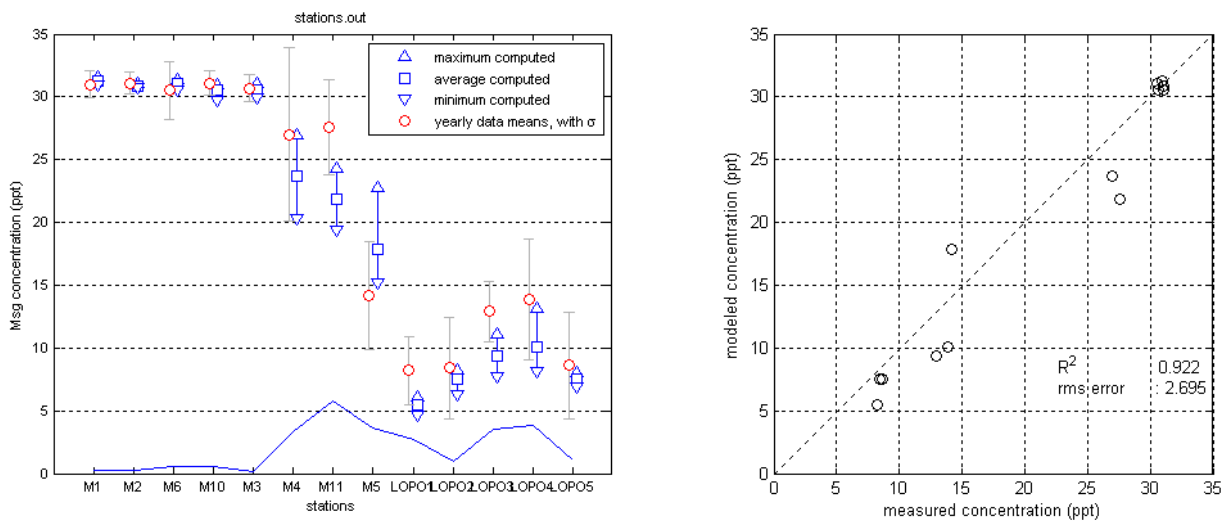

Figure VI-5. Comparison of measured and calibrated model output at stations in Madaket Harbor System. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

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

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

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

sub-embayment	present load (kg/day)	build out (kg/day)	build out % change	no load (kg/day)	no load % change
Madaket Harbor	0.663	0.877	32.2%	0.238	-64.0%
Hither Creek	4.041	4.384	8.5%	0.425	-89.5%
Madaket Ditch	2.433	2.808	15.4%	0.507	-79.2%
Long Pond	3.230	3.400	5.3%	0.142	-95.6%
North Head Long Pond	0.238	0.378	58.6%	0.145	-39.1%

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be more than a 5.3% increase in watershed nitrogen load to the Long Pond as a result of potential future development. Other watershed areas would experience larger load increases, for example the loads to North Head Long Pond would increase 58.6% from the present day loading levels. For the no load scenario, a majority of the load entering the watershed is removed; therefore, the load is generally lower than existing conditions by over 60% overall, except for North Head Long Pond.

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

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

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

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,

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

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Madaket Harbor	0.877	8.603	17.952
Hither Creek	4.384	0.534	-0.729
Madaket Ditch	2.808	-	0.061
Long Pond	3.400	0.975	3.283
North Head Long Pond	0.378	0.693	0.995

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of Madaket Harbor System was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). 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 the upper portion of the system, with the largest change occurring in the North Head Long Pond (3.3%) and the least change occurring in Madaket Harbor (0.1%). Color contours of model output for the build-out scenario are present in Figure VI-7. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-4, which allows direct comparison of nitrogen concentrations between loading scenarios.

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

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Madaket Harbor	M1	0.3107	0.3110	0.1%
Madaket Harbor	M2	0.3205	0.3210	0.2%
Madaket Harbor	M3	0.3280	0.3290	0.3%
Hither Creek	M4	0.4639	0.4736	2.1%
Hither Creek	M5	0.6130	0.6317	3.1%
Madaket Harbor	M6	0.3161	0.3166	0.2%
Madaket Harbor	M10	0.3266	0.3275	0.3%
Hither Creek	**M11**	**0.5107**	**0.5233**	**2.5%**
Long Pond	LOPO1	1.0394	1.0707	3.0%
Long Pond	LOPO2	0.9827	1.0129	3.1%
Long Pond	LOPO3	0.8821	0.9097	3.1%
Long Pond	LOPO4	0.8515	0.8783	3.1%
North Head Long Pond	LOPO5	0.8937	0.9234	3.3%

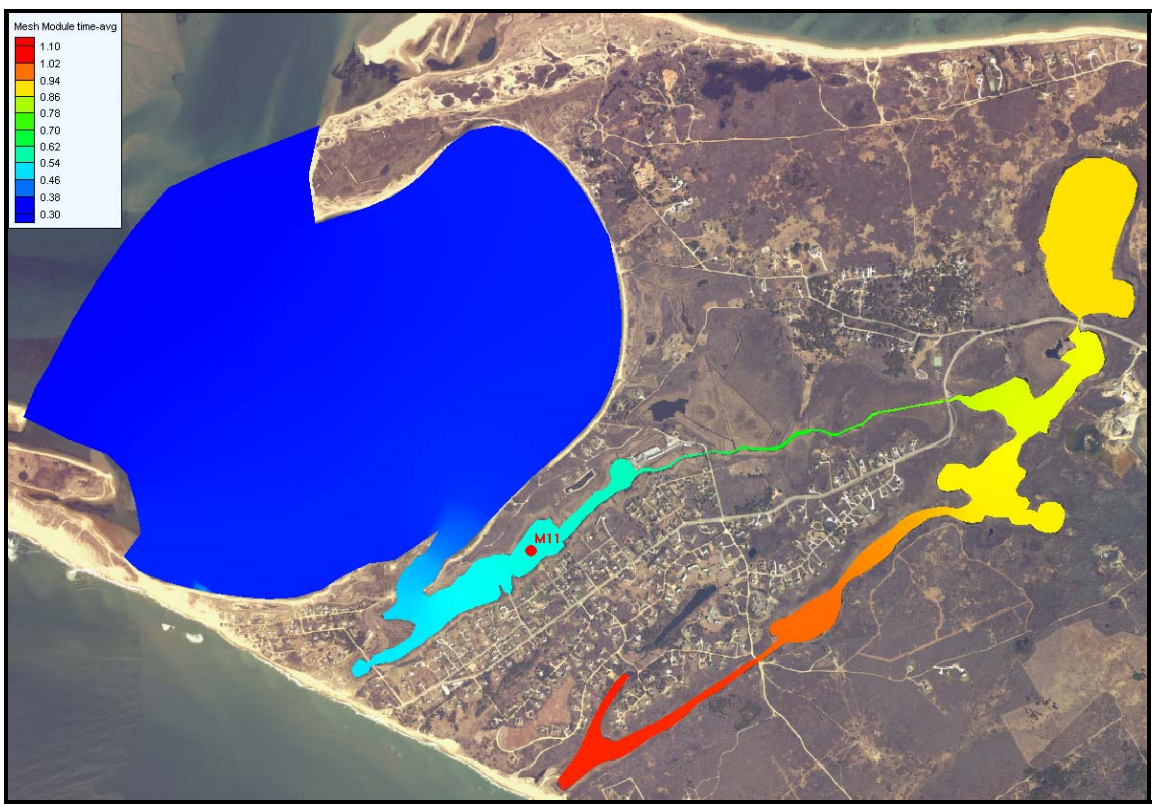

Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in Madaket Harbor System, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Madaket Harbor System (M11) is shown.

VI.2.6.2 No Anthropogenic Load

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

Table VI-7. "No anthropogenic loading" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of Madaket Harbor System, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Madaket Harbor	0.238	8.603	17.485
Hither Creek	0.425	0.534	-0.438
Madaket Ditch	0.507	-	0.030
Long Pond	0.142	0.975	1.751
North Head Long Pond	0.145	0.693	0.498

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-8, with reductions ranging from 1% occurring in Madaket Harbor to greater than 40% within Long Pond. Results for each system are shown pictorially in Figure VI-8.

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

Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Madaket Harbor	M1	0.3107	0.3080	-0.9%
Madaket Harbor	M2	0.3205	0.3150	-1.7%
Madaket Harbor	M3	0.3280	0.3186	-2.9%
Hither Creek	M4	0.4639	0.3654	-21.2%
Hither Creek	M5	0.6130	0.4231	-31.0%
Madaket Harbor	M6	0.3161	0.3115	-1.5%
Madaket Harbor	M10	0.3266	0.3181	-2.6%
Hither Creek	**M11**	**0.5107**	**0.3819**	**-25.2%**
Long Pond	LOPO1	1.0394	0.6029	-42.0%
Long Pond	LOPO2	0.9827	0.5800	-41.0%
Long Pond	LOPO3	0.8821	0.5430	-38.4%
Long Pond	LOPO4	0.8515	0.5317	-37.6%
North Head Long Pond	LOPO5	0.8937	0.5651	-36.8%

Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in Madaket Harbor System, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Madaket Harbor System (M11) is shown.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Madaket Harbor and Long Pond embayment system in the Town of Nantucket, MA, our assessment is based upon data from the water quality monitoring baseline developed by the Nantucket Marine Department and MassDEP and MEP surveys of eelgrass distribution, benthic animal communities and sediment characteristics, and dissolved oxygen and chlorophyll a records conducted during the summer and fall of 2003. 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 (Chapter 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 threshold determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll a (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed dissolved oxygen sensors throughout the Madaket Harbor-Long Pond Estuary at points that would be representative of dissolved oxygen conditions at critical locations in the system, namely the main basin of Madaket Harbor, Hither Creek (a tributary basin to Madaket Harbor), and three moorings in the brackish water basins of Long Pond and North Head of Long Pond. One DO mooring was deployed in the southern portion of Long Pond south of the Massasoit Bridge, a second mooring was deployed in the upper portion of Long Pond near Jeremy Cove and a third DO mooring was positioned in the North Head of Long Pond. The five dissolved oxygen moorings were deployed to record the frequency and duration of low oxygen conditions and chlorophyll a levels during the critical summer period. The MEP habitat analysis uses eelgrass as a key indicator species for 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 Madaket Harbor system (specifically the Harbor and Hither Creek discharging to the Harbor) was conducted for comparison to historic records (MassDEP Eelgrass Mapping Program, C. Costello). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern

Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the Madaket Harbor system, temporal changes in eelgrass distribution provide a strong basis for evaluating the effects of recent increases in nitrogen loading to Hither Creek and Madaket Harbor. It is not just the area of eelgrass coverage, but the temporal trends that are key to determining the habitat quality within these marine basins. The brackish water basins of Long Pond and North Head of Long Pond are wetland dominated basins with no history of eelgrass, as is expected from their relatively low salinities.

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

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 4 mg L^{-1}, in open water estuarine environments. Massachusetts State Water Quality Classifications indicate that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Madaket Harbor system are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality. It is through the MEP and TMDL processes that management actions are developed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Madaket Harbor and Long Pond system (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during

each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September, during the summer of 2003.

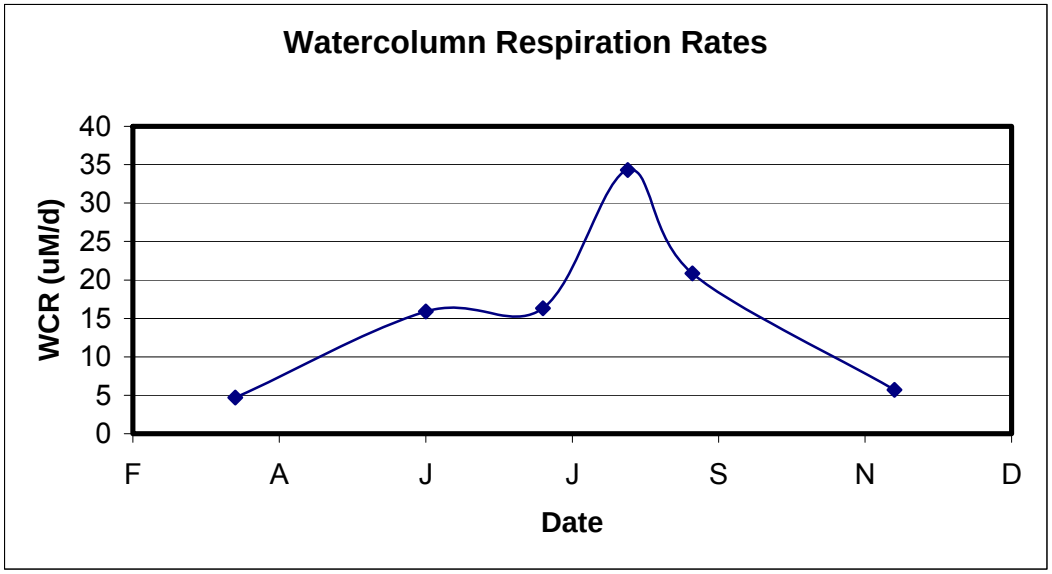

Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

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

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

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate nutrient enriched waters within Madaket Harbor-Long Pond System. However, the degree of enrichment and subsequent effect on habitat quality varied widely between the System's sub-basins. Madaket Harbor, which functions as a open marine basin generally showed only moderate declines in oxygen consistent with the moderate amount of phytoplankton biomass (chlorophyll a) in its waters (Figures VII-3, VII-8). In contrast, Hither Creek had periodic phytoplankton blooms and bottom water hypoxia (Figures VII-4, VII-9), while

Figure VII-2. Aerial Photograph of the Madaket Harbor / Long Pond system on the Island of Nantucket showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2003. It should be noted that the breach through the sand spit south of Madaket Harbor as depicted in the aerial photograph no longer exists and did not exist during the DO mooring deployment.

Long Pond had even higher chlorophyll a levels and more frequent hypoxia (Figures VII-6, VII-7, VII-10, VII-11, VII-12). The North Head of Long Pond exchanges water with Long Pond through a culvert but appears to be functioning somewhat independently from Long Pond. The North Head generally supports moderate chlorophyll a levels and bottom water oxygen above 6 mg L-1 and no observed hypoxic events. (Figures VII-5, VII-10). The wetland dominated nutrient enriched basin of Long Pond also showed large diurnal shifts in bottom water oxygen at both mooring sites. While periodically hypoxic in darkness, during day light hours oxygen levels frequently reached 2-3 time atmospheric equilibration. In the case of Hither Creek and Long Pond specifically (exclusive of the North Head of Long Pond) the oxygen data is consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll a. The measured levels of oxygen depletion and enhanced chlorophyll a levels follows the spatial pattern of total nitrogen levels in this portion of the overall system (Chapter VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of the Long Pond and Hither Creek portions of the estuarine system.

The oxygen records show that the tidally restricted brackish water wetland basin of Long Pond has the largest daily oxygen excursions, a nutrient related response. 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. Within Long Pond oxygen levels frequently exceeded 10 mg L^{-1} in daytime and 3 mg L^{-1} to less than 2 mg L^{-1} at night. The clear evidence of oxygen levels above atmospheric equilibration indicates that these reaches of the Madaket Harbor / Long Pond system are nitrogen and organic matter enriched. However, Long Pond is a brackish basin with a small tidal range and extensive wetlands, particularly in its northern reach. Wetlands are naturally nutrient and organic matter enriched and typically show wide variation in oxygen. Assessment of the habitat quality of each basin must relate to the basin's functional type (salt marsh, open water, tidal river, etc.). The observed water quality results must be viewed in this light. The embayment specific results are as follows:

Madaket Harbor (Figures VII-3 and VII-8):

One dissolved oxygen mooring was deployed in Madaket Harbor in order to determine potential oxygen depletion of bottom waters under worst case conditions of the summer. At the time of the mooring deployment in 2003, inflowing water from Nantucket Sound and the Atlantic Ocean entered the Madaket Harbor from the west, though that circulation is known to change periodically due to openings through the southern barrier spit that occur as a result of intense winter storms (e.g. Figure VII-2 shows a small opening to the south that opened in April 2007, which has recently closed). Positive effects on dissolved oxygen in Madaket Harbor would result from enhanced flushing with clean, oxygen rich water from offshore waters while negative effects would be driven by low oxygen water discharging to Madaket Harbor from Hither Creek. The dissolved oxygen mooring was positioned in order to balance these competing influences and obtain a realistic measure of the oxygen characteristics of the harbor. Dissolved oxygen in Madaket Harbor showed a classic diurnal quality of lower DO levels in the early morning hours and higher concentrations later during the day, however the range of the excursion was not generally large and the level of oxygen depletion was relatively small. Oxygen levels were almost always greater than 5 mg L^{-1} (95% of time). The outer portion of Harbor basin had only a single record below 6 mg/L (e.g. 5.9 mg/L) in the multi years of water quality monitoring. The nearshore oxygen values, while generally above 6 mg/L, had minimum oxygen records of 5.2

mg/L. Overall, oxygen depletion of bottom waters within the main basin of Madaket Harbor appears to be a rare event and the levels of depletion small. Similarly, the chlorophyll a levels were generally low for a coastal basin in the region, averaging 5.2 ug/L over the deployment. While higher levels were found at the end of the deployment, chlorophyll a never exceeded 14 ug/L, with levels <5 ug/L 64% of the time. Average chlorophyll a levels from the NWQMP were low, averaging between 3.3 ug L^{-1} and 5.3 ug L-1, over the multi-year monitoring. Both the DO and chlorophyll records are consistent with only a slight enrichment of nitrogen and phytoplankton within this basin and generally levels indicative of a non-nutrient impaired basin.

Hither Creek (Figures VII-4 and VII-9):

In contrast to oxygen and chlorophyll a levels in the adjacent main basin of Madaket Harbor, Hither Creek oxygen and chlorophyll a levels are indicative of a nitrogen and organic matter enriched basin. The continuously recording sensors were placed midway between the inlet and the mouth of Madaket Ditch in Hither Creek (Figure VII-2). The main channel of Hither Creek was created by dredging several decades ago (post-1951), likely associated with the development of the marina at the head of the Creek. As such, a depositional basin now exists which presently supports very soft organic rich mud. Oxygen levels within Hither Creek frequently declined below 4 mg L^{-1} and 3 mg L^{-1}, 45% and 25% of the time, respectively but infrequently below 2 mg L^{-1}. Chlorophyll a levels were significantly elevated in Hither Creek over Madaket Harbor, with an average of 12 ug L^{-1}, and were >10 ug L^{-1} 58% of the time, with blooms >20 ug L^{-1}. These elevated levels of phytoplankton are consistent with the periodic bottom water hypoxia recorded during the deployment period. Results of the Nantucket Water Quality Monitoring Program (NWQMP) are consistent with the mooring results and show minimum oxygen levels slightly greater above 3 mg L^{-1} and average chlorophyll a levels between 8 ug $L-^{1}$ and 10 ug L^{-1}. The periodic hypoxia, elevated chlorophyll levels which reduces light penetration, and sediment characteristics are all consistent with a nitrogen enriched basin which has lost eelgrass in recent decades. The oxygen and chlorophyll a data indicate that Hither Creek habitats are likely presently impaired by nutrient enrichment.

Long Pond-North Head Basin Upper (Figures VII-5 and VII-10):

The mooring deployed in the North Head of Long Pond (Long Pond Upper) was located in relatively shallow water (Figure VII-2). This basin is brackish (9 ppt) with fringing wetlands. The basin is tidally restricted and receives tidal flows via Madaket Ditch and the culvert to Long Pond. Although total nitrogen levels are high for an embayment, these measured values are typical for an enclosed basin with wetlands. The oxygen record shows levels $\geq$6 mg L^{-1}, 90% of the time and rarely decline below 5 mg L^{-1} (Table VII-1). Consistent with the oxygen conditions, chlorophyll a levels were only moderately elevated, generally between 5 ug L^{-1} and 10 ug L^{-1}, without significant blooms. Fundamentally, the dissolved oxygen record is consistent with the low chlorophyll concentrations. As a functional wetland basin, the oxygen and chlorophyll a levels suggest little impairment.

Long Pond Middle (Figures VII-6 and VII-11)

The Long Pond Middle mooring was located at the mouth of Jeremy Cove in the main channel of Long Pond, south of the discharge of Long Pond to Madaket Ditch (Figure VII-2). This portion of the Long Pond basin is dominated by fringing wetlands. Oxygen depletion was large and frequent, generally following the diurnal light/dark cycle. In addition to frequent daily declines to <2 mg L^{-1} large daily excursions were observed with daytime oxygen levels frequently rising to 2-3 times air equilibration. Oxygen levels were below 4 mg L^{-1}, 31% of the

record and below 3 mg L^{-1} 24% of the record (Table VII-1). Although wetland channels periodically are hypoxic/anoxic at night, the large daily oxygen excursions are atypical and indicate an impairment. Consistent with the oxygen levels, chlorophyll a levels were very high, averaging 43 ug L^{-1} with blooms exceeding 80 ug L^{-1} (Table VII-2). The Nantucket Water Quality Monitoring Program observed similarly high chlorophyll a levels, averaging 25 ug L^{-1} over the multiyear program. The oxygen and chlorophyll a data indicate that while the middle portion of Long Pond is a wetland dominated basin and therefore naturally nutrient and organic matter enriched, none-the-less the large phytoplankton blooms coupled with the large oxygen excursions suggest that it is currently beyond its nutrient assimilative capacity.

Long Pond Lower (Figures VII-7 and VII-12)

The Long Pond Lower mooring was located in the southernmost reach of Long Pond, closest to the barrier beach that separates Long Pond from the Atlantic Ocean (south of the Massasoit Bridge, Figure VII-2).

Oxygen levels reflected the nutrient and organic rich nature of this system, but without the prolonged hypoxia, large daily excursions and very large phytoplankton blooms found within the mid basin. However, periodic hypoxia/anoxia was observed with declines below 4 mg L^{-1} and 3 mg L^{-1} found 16% and 11% of the time (Table VII-2). Oxygen levels were typically <6 mg L-1 (63% of time). Daytime levels rarely exceeded 1.5 times air equilibration, reflecting the chlorophyll a levels. Chlorophyll levels were moderately high throughout the mooring record, averaging 15.9 ug L-1 but infrequently exceeded 25 ug L-1. While these levels are elevated, they are ~1/3 lower than found in the mid basin. While Long Pond, overall, has significant wetland influence and therefore is naturally enriched in nutrients and organic matter, the chlorophyll a, and to a lesser extent oxygen records, indicate that this lower basin is also beyond its nutrient assimilative capacity.

Overall, the oxygen and chlorophyll a levels within the Madaket Harbor - Long Pond System indicate little to no impairment of the outer harbor, consistent with its nitrogen level (tidally averaged TN <0.33 mg L^{-1}). All parameters reflect a basin not presently impaired by nitrogen enrichment. In contrast, Hither Creek which receives high quality waters on the flooding tide from Madaket Harbor, but nutrient and organic matter enrichment from its watershed inputs and from the upper estuarine reaches via Madaket Ditch, has oxygen declines and chlorophyll levels consistent with its tidally averaged TN of 0.51 mg L^{-1} (Chapter VI), indicating nitrogen related habitat impairment. The upper reaches of the system, Long Pond and North Head of Long Pond are brackish wetland influenced systems that are naturally enriched with nutrients and organic matter. The North Head of Long Pond supported generally high oxygen conditions and moderate chlorophyll a levels and a high tidally averaged TN (0.89 mg L^{-1}). Based upon the functional type of basin, the oxygen and chlorophyll a levels are indicative of high quality to possibly slightly impaired habitat. In contrast, the wetland dominated Long Pond basin is presently showing wide oxygen excursions, frequent hypoxia/anoxia and very high chlorophyll levels indicating that even this naturally enriched system is receiving external nitrogen loading that are resulting in habitat impairments, with tidally averaged TN levels that are clearly elevated (0.85-1.0 mg TN L^{-1}).

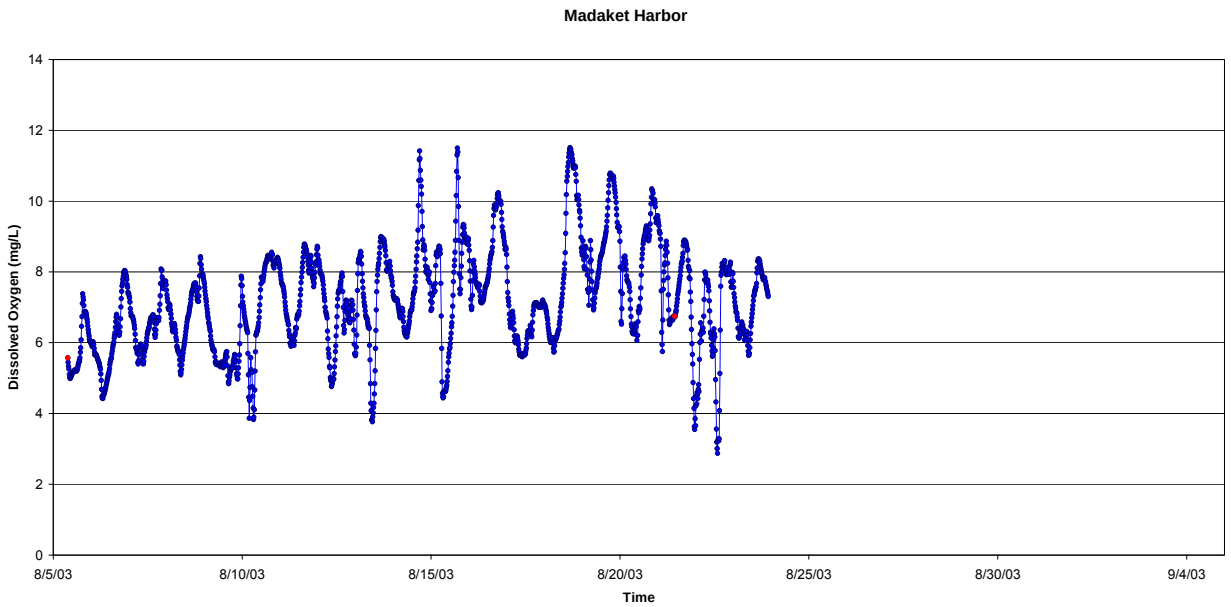

Figure VII-3. Bottom water record of dissolved oxygen at the Madaket Harbor station, Summer 2003. Calibration samples represented as red dots. Shortened record due to instrument failure.

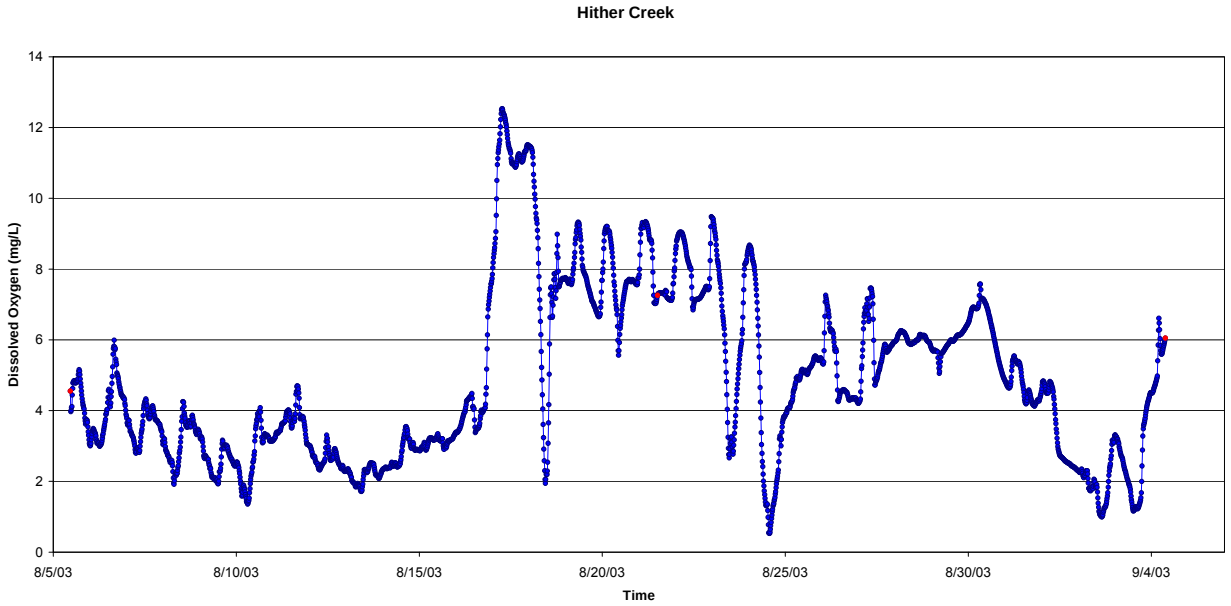

Figure VII-4. Bottom water record of dissolved oxygen at the Hither Creek station, Summer 2003. Calibration samples represented as red dots.

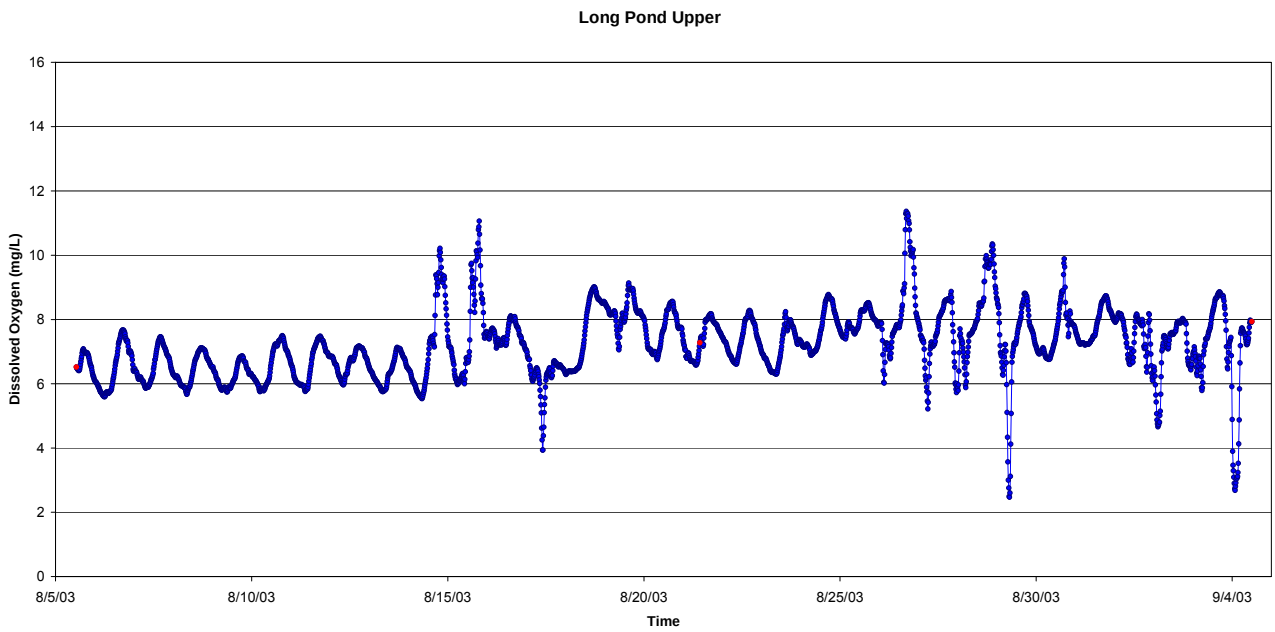

Figure VII-5. Bottom water record of dissolved oxygen at the Long Pond Upper station located in the North Head of Long Pond, Summer 2003. Calibration samples represented as red dots.

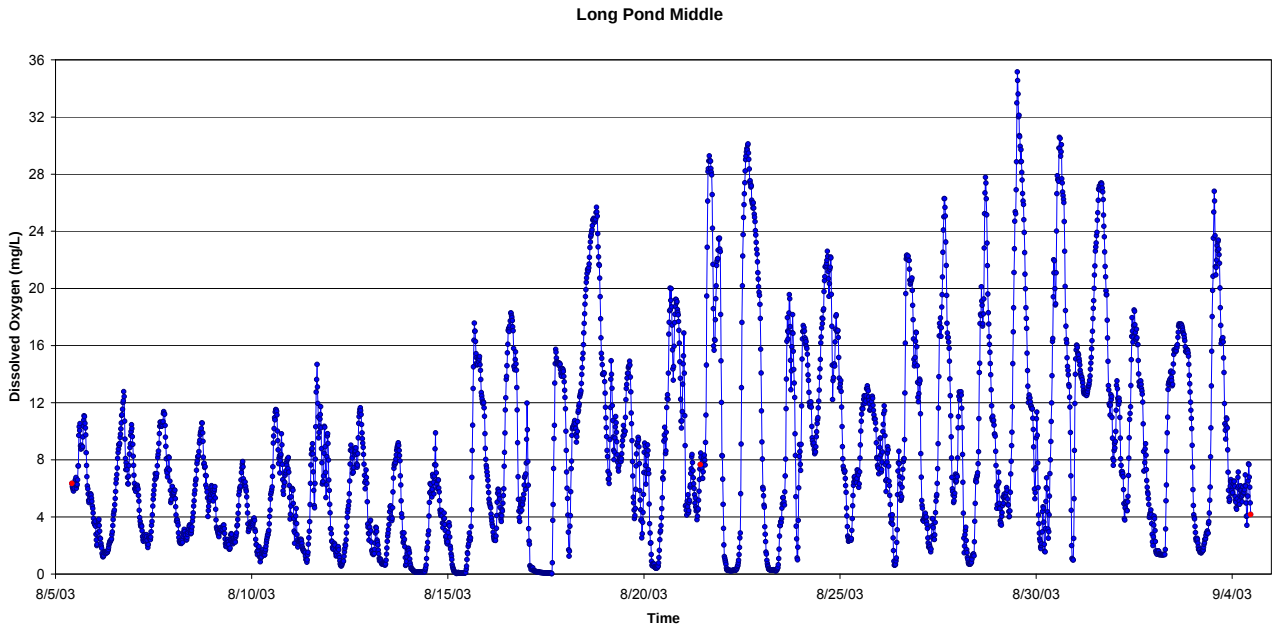

Figure VII-6. Bottom water record of dissolved oxygen at the Long Pond Middle station, Summer 2003. Calibration samples represented as red dots.

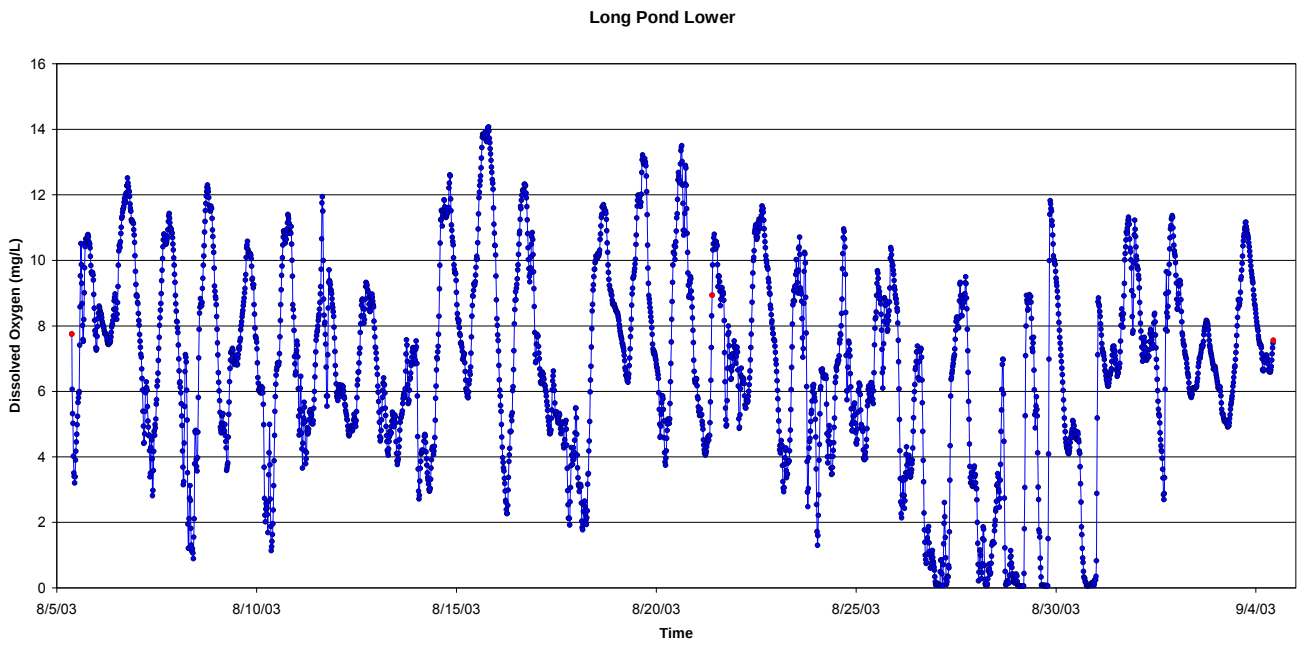

Figure VII-7. Bottom water record of dissolved oxygen at the Long Pond Lower station, Summer 2003. Calibration samples represented as red dots.

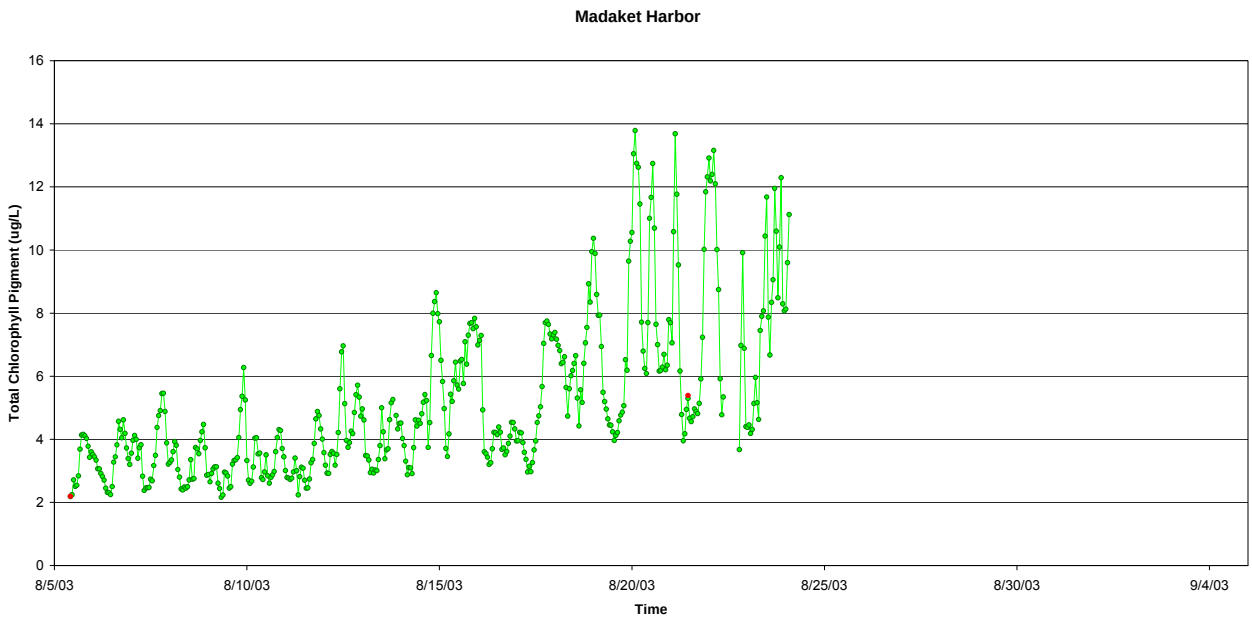

Figure VII-8. Bottom water record of Chlorophyll-*a* at the Madaket Harbor station, Summer 2003. Calibration samples represented as red dots.

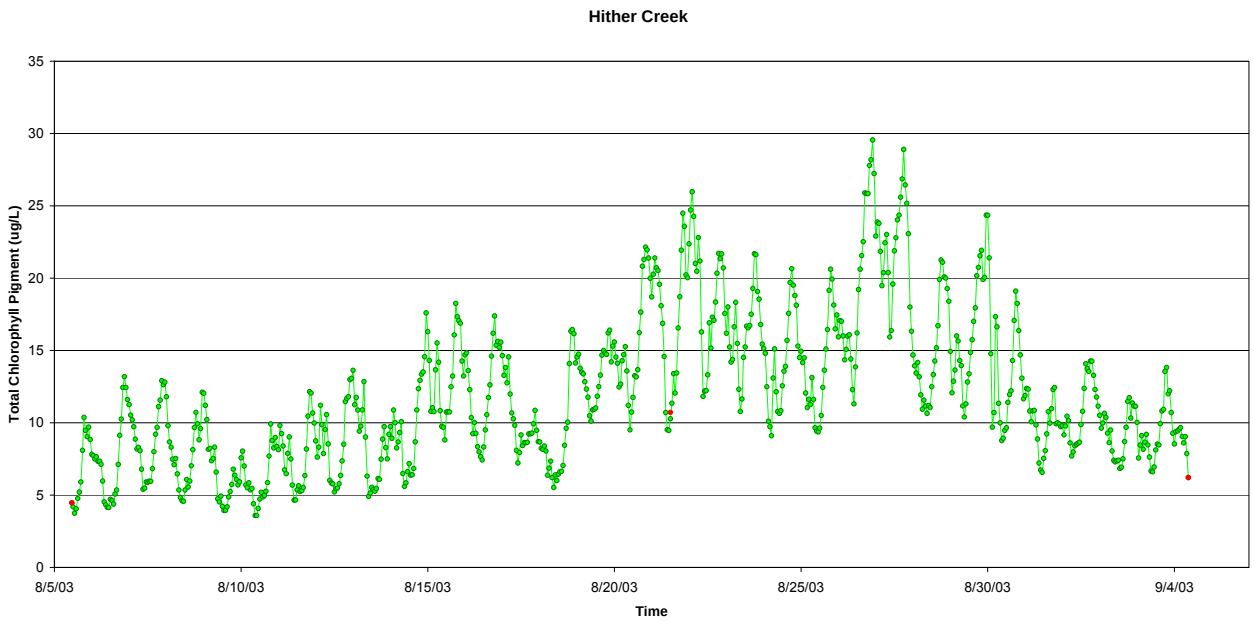

Figure VII-9. Bottom water record of Chlorophyll-*a* at the Hither Creek station, Summer 2003. Calibration samples represented as red dots.

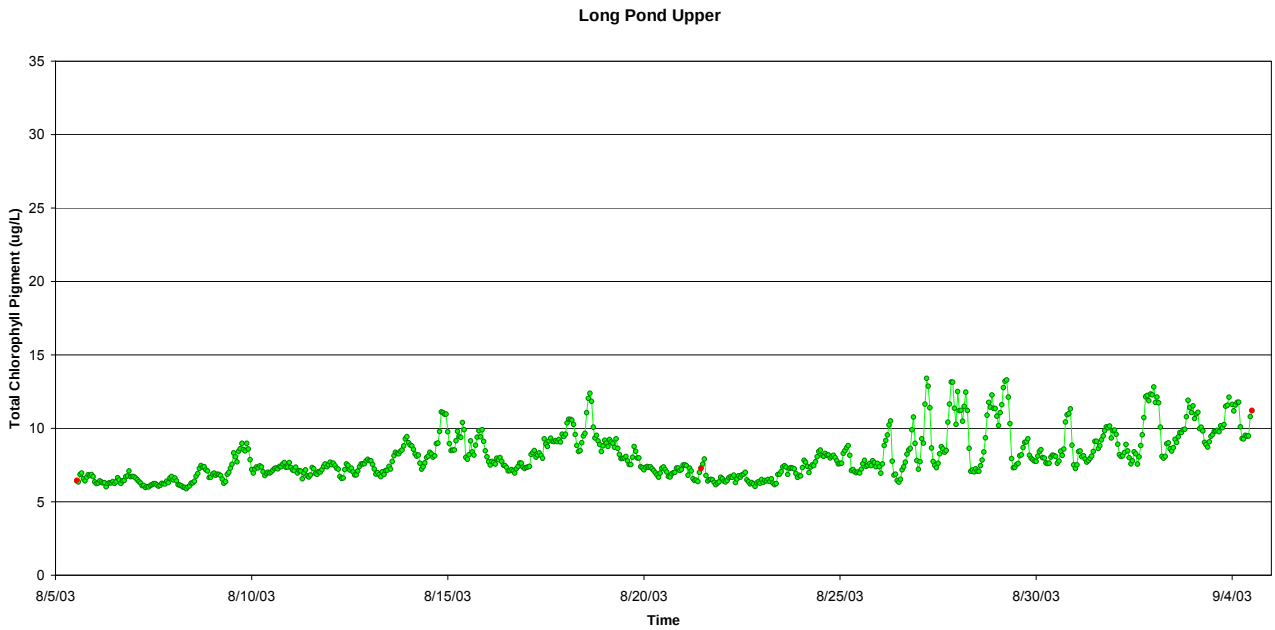

Figure VII-10. Bottom water record of Chlorophyll-*a* at the Long Pond Upper station, Summer 2003. Calibration samples represented as red dots.

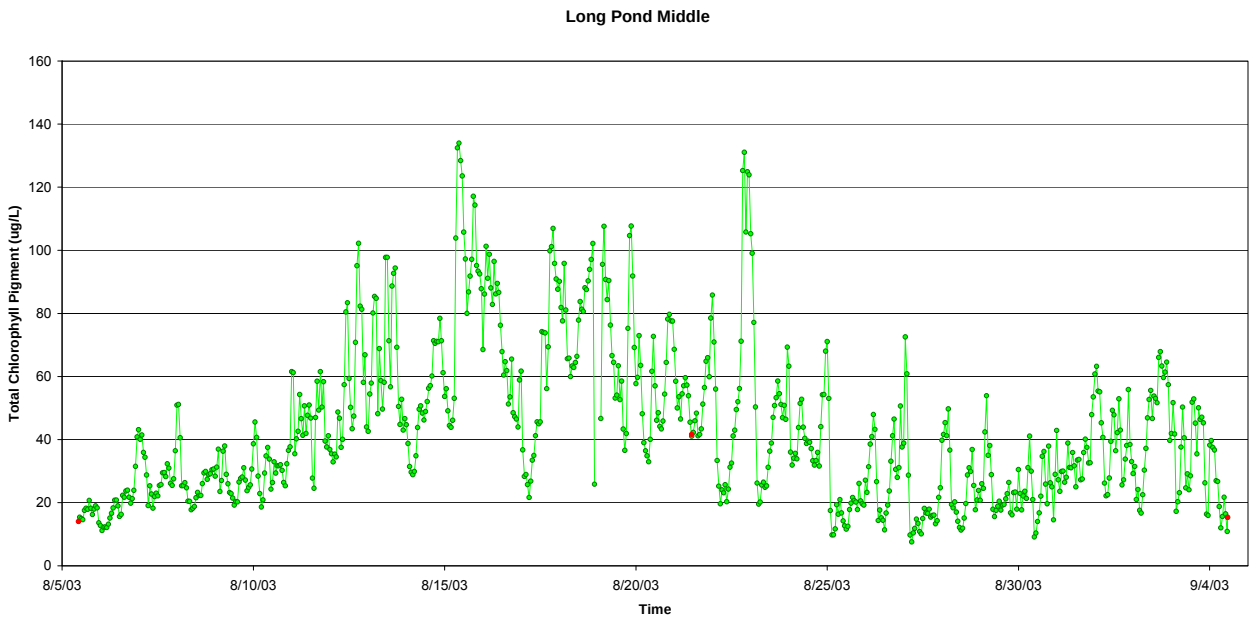

Figure VII-11. Bottom water record of Chlorophyll-*a* at the Long Pond Middle station, Summer 2003. Calibration samples represented as red dots.

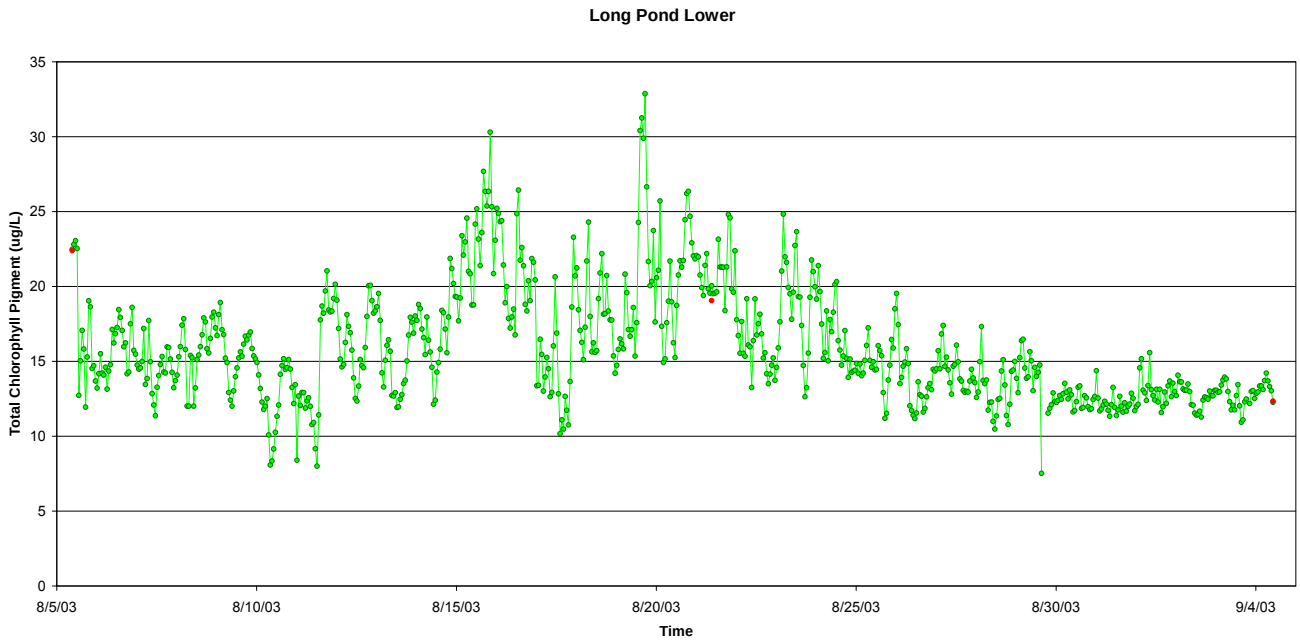

Figure VII-12. Bottom water record of Chlorophyll-*a* at the Long Pond Lower station, Summer 2003. Calibration samples represented as red dots.

Table VII-1. Days and percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels.

Station	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)
Madaket, Nantucket	**8/5/2003**	**8/24/2003**	**18.7**	**21%**	**5%**	**1%**	**0%**
			18.7	3.90	1.00	0.20	0.01
			Mean	0.18	0.09	0.04	0.01
			Min	0.01	0.01	0.01	0.01
			Max	0.75	0.18	0.08	0.01
			S.D.	0.18	0.06	0.03	NA
Hither Creek, Nantucket	**8/5/2003**	**9/4/2003**	**29.9**	**70%**	**59%**	**45%**	**25%**
			29.9	21.04	17.53	13.31	7.61
			Mean	1.75	1.59	0.95	0.38
			Min	0.01	0.01	0.05	0.01
			Max	11.38	10.08	4.52	2.04
			S.D.	3.27	3.00	1.26	0.53
Long Pond Upper, Nantucket	**8/5/2003**	**9/4/2003**	**30.0**	**10%**	**1%**	**1%**	**0%**
			30.0	3.03	0.42	0.25	0.09
			Mean	0.15	0.10	0.08	0.05
			Min	0.01	0.06	0.02	0.04
			Max	0.40	0.19	0.16	0.05
			S.D.	0.12	0.06	0.07	0.01
Long Pond Middle, Nantucket	**8/5/2003**	**9/4/2003**	**30.1**	**44%**	**37%**	**31%**	**24%**
			30.1	13.16	11.01	9.33	7.34
			Mean	0.22	0.22	0.21	0.18
			Min	0.01	0.01	0.01	0.01
			Max	0.83	0.81	0.69	0.67
			S.D.	0.24	0.23	0.22	0.18
Long Pond Lower, Nantucket	**8/5/2003**	**9/4/2003**	**30.1**	**37%**	**27%**	**16%**	**11%**
			30.1	11.26	8.02	4.96	3.30
			Mean	0.24	0.17	0.13	0.14
			Min	0.01	0.01	0.01	0.01
			Max	0.90	0.80	0.78	0.65
			S.D.	0.23	0.18	0.18	0.19

Table VII-2. Duration (days and % 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.

Station	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)
Madaket, Nantucket	**8/5/2003**	**8/24/2003**	**18.7**	**36.1%**	**6.9%**	**0.0%**	**0.0%**	**0.0%**
Mean Chl Value = 5.12 ug/L			18.7	6.75	1.29	0.00	0.00	0.00
			Mean	0.36	0.14	N/A	N/A	N/A
			Min	0.04	0.04	0.00	0.00	0.00
			Max	1.50	0.38	0.00	0.00	0.00
			S.D.	0.39	0.12	N/A	N/A	N/A
Hither Creek, Nantucket	**8/5/2003**	**9/4/2003**	**29.9**	**95.6%**	**57.7%**	**24.1%**	**9.8%**	**1.8%**
Mean Chl Value = 11.96 ug/L			29.9	28.58	17.25	7.21	2.92	0.54
			Mean	3.57	0.54	0.31	0.22	0.18
			Min	0.04	0.04	0.04	0.04	0.04
			Max	21.96	4.58	1.50	0.58	0.29
			S.D.	7.45	0.93	0.34	0.18	0.13
Long Pond Upper, Nantucket	**8/5/2003**	**9/4/2003**	**30.0**	**99.7%**	**12.6%**	**0.0%**	**0.0%**	**0.0%**
Mean Chl Value = 8.12 ug/L			30.0	29.92	3.79	0.00	0.00	0.00
			Mean	14.96	0.24	N/A	N/A	N/A
			Min	0.04	0.04	0.00	0.00	0.00
			Max	29.88	0.63	0.00	0.00	0.00
			S.D.	21.10	0.19	N/A	N/A	N/A
Long Pond Middle, Nantucket	**8/5/2003**	**9/4/2003**	**30.1**	**99.9%**	**99.3%**	**94.1%**	**83.9%**	**73.4%**
Mean Chl Value = 43.2 ug/L			30.1	30.08	29.88	28.33	25.25	22.08
			Mean	15.04	5.98	2.02	0.79	0.61
			Min	0.04	0.04	0.04	0.04	0.04
			Max	30.04	19.50	18.75	11.83	5.58
			S.D.	21.21	7.79	4.95	2.08	1.19
Long Pond Lower, Nantucket	**8/5/2003**	**9/4/2003**	**30.1**	**99.3%**	**98.3%**	**49.7%**	**14.4%**	**2.4%**
Mean Chl Value = 15.88 ug/L			30.1	29.88	29.58	14.96	4.33	0.71
			Mean	14.94	4.93	0.30	0.14	0.10
			Min	0.04	0.04	0.04	0.04	0.04
			Max	29.83	18.08	2.42	0.75	0.25
			S.D.	21.07	6.89	0.49	0.16	0.09

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data were conducted for the Madaket Harbor and Long Pond Embayment System by the MassDEP Eelgrass Mapping Program as part of the MEP . Surveys were conducted in 1995, 2001 and 2006. Additional analysis of available aerial photos from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. The 1995, 2001 and 2006 maps were field validated by MassDEP. Validation of the 1951 coverage was conducted, as possible, by the MEP Technical Team using available reports, and historical land-use analysis. The primary use of the data is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts in coverage have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995, 1995 to 2001 and 2001 to 2006 (Figure VII-13); the period in which watershed nitrogen loading significantly increased to its present level. This temporal information can be used to determine the stability of the eelgrass community. In addition to the mapping completed by the MassDEP, confirmation of eelgrass presence and density was also undertaken during MEP field data collection efforts in the summer of 2003 (Figure VII-14).

At present, eelgrass coverage is extensive and stable throughout the main portion of Madaket Harbor. The 1951-2006 coverages indicate a high quality eelgrass habitat, consistent with the oxygen and chlorophyll levels (see above) and the low level of nitrogen enrichment of Harbor waters (tidally averaged TN <0.33 mg L^{-1}). Based on the 1995 MassDEP eelgrass survey, the existing beds have increased significantly relative to the estimate from 1951. However, from 1995 to 2006 there may have been a slight reduction in coverage, but it is less than 10% from the 1995 coverage and is at the limits of detection, particularly when the analysis shows no change from 2001 to 2006. Given variations in the circulation of the Harbor over this time period (breach opening and closing) it is not possible to infer a change in area at this time, and certainly not a continuous decline.

The temporal pattern of eelgrass coverage in Hither Creek contrasts strongly with the main basin of Madaket Harbor (Table VII-3). In 1951, eelgrass beds covered much of the main basin (to water quality station M11). However, by 1995 the beds had been significantly reduced and limited to the margins of the basin and no eelgrass was found in the 2001 and 2006 MassDEP surveys and the MEP 2003 observations. The MEP Technical Team has determined that the marina at the head of Hither Creek was constructed between the 1951 and 1995 surveys and that a navigation channel was dredged through the inlet to the marina, deepening this portion of the basin. However, the loss of eelgrass cannot be ascribed to the channel being deepened, as the fringing beds persisted until 1995 as did the small bed in the lower basin that does not appear to have been deepened. The recent loss of the 1995 beds coupled with measured periodic hypoxia and high chlorophyll a levels supports the contention that nitrogen enrichment (tidally averaged TN of 0.51 mg L^{-1} at station M11 at the inland edge of the 1951 beds) caused the decline in eelgrass habitat.

In contrast to the more marine basins of this estuary, the Long Pond basins do not appear to have eelgrass habitat, as there is not present or historical evidence of eelgrass within their basins. As a result eelgrass restoration within these brackish water basins cannot be supported as a nutrient management objective. However, the loss of eelgrass from Hither Creek from 1951-1995 and 1995 to 2001/2006, and the present absence of this habitat from this basin, coupled to the present level of nitrogen enrichment, make restoration of this key estuarine

resource a primary target for nitrogen management within the Madaket Harbor-Long Pond Embayment System.

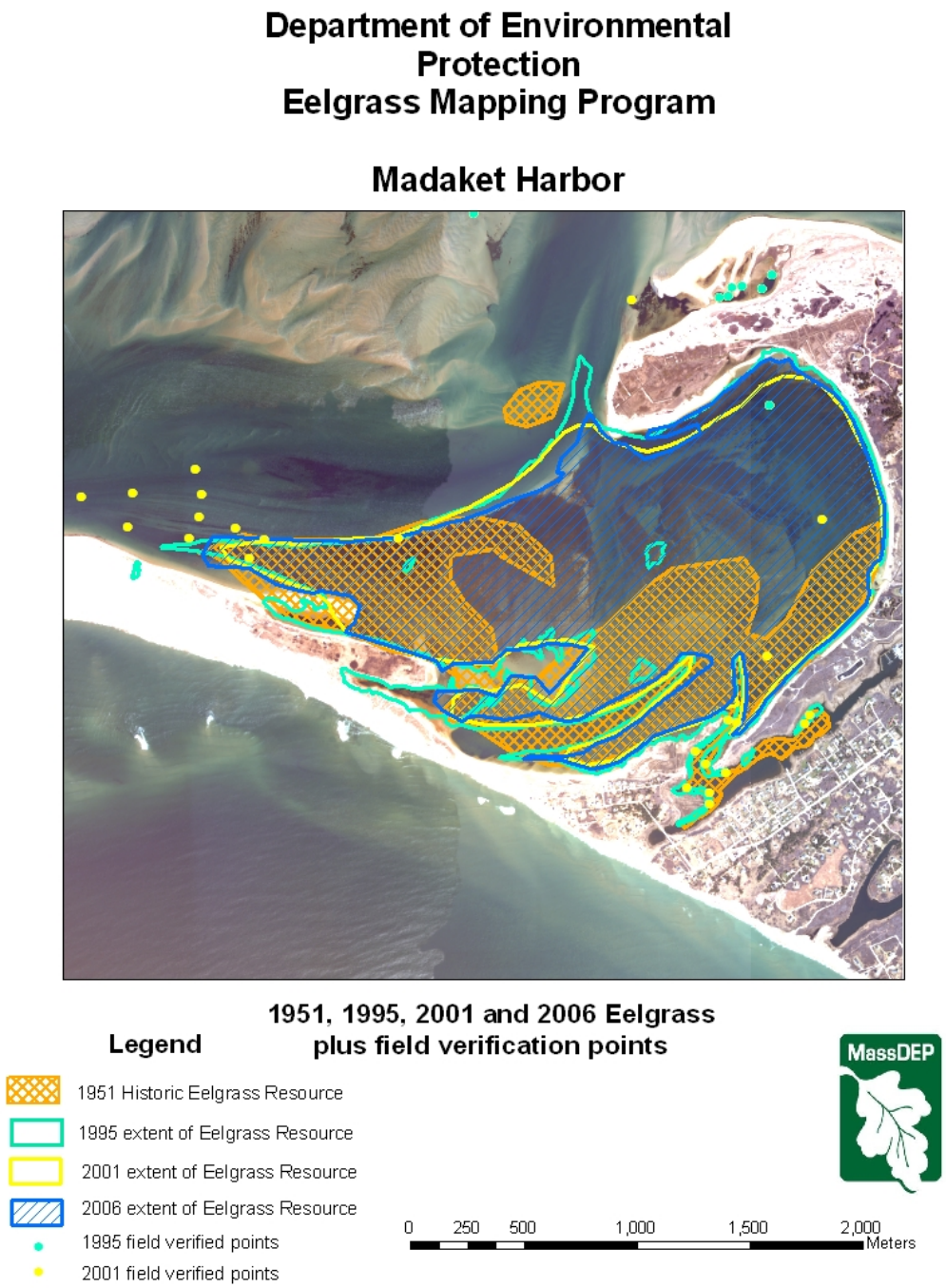

Figure VII-13. Eelgrass bed distribution within the Madaket Harbor System. The 1995 coverage is depicted by the green outline which circumscribes the eelgrass beds. Similarly, the yellow and blue lines indicate eelgrass areas mapped in 2001 and 2006, respectively. the orange lines indicate areas determined from 1951 ortho-photos. All data was provided by the MassDEP Eelgrass Mapping Program (C. Costello).

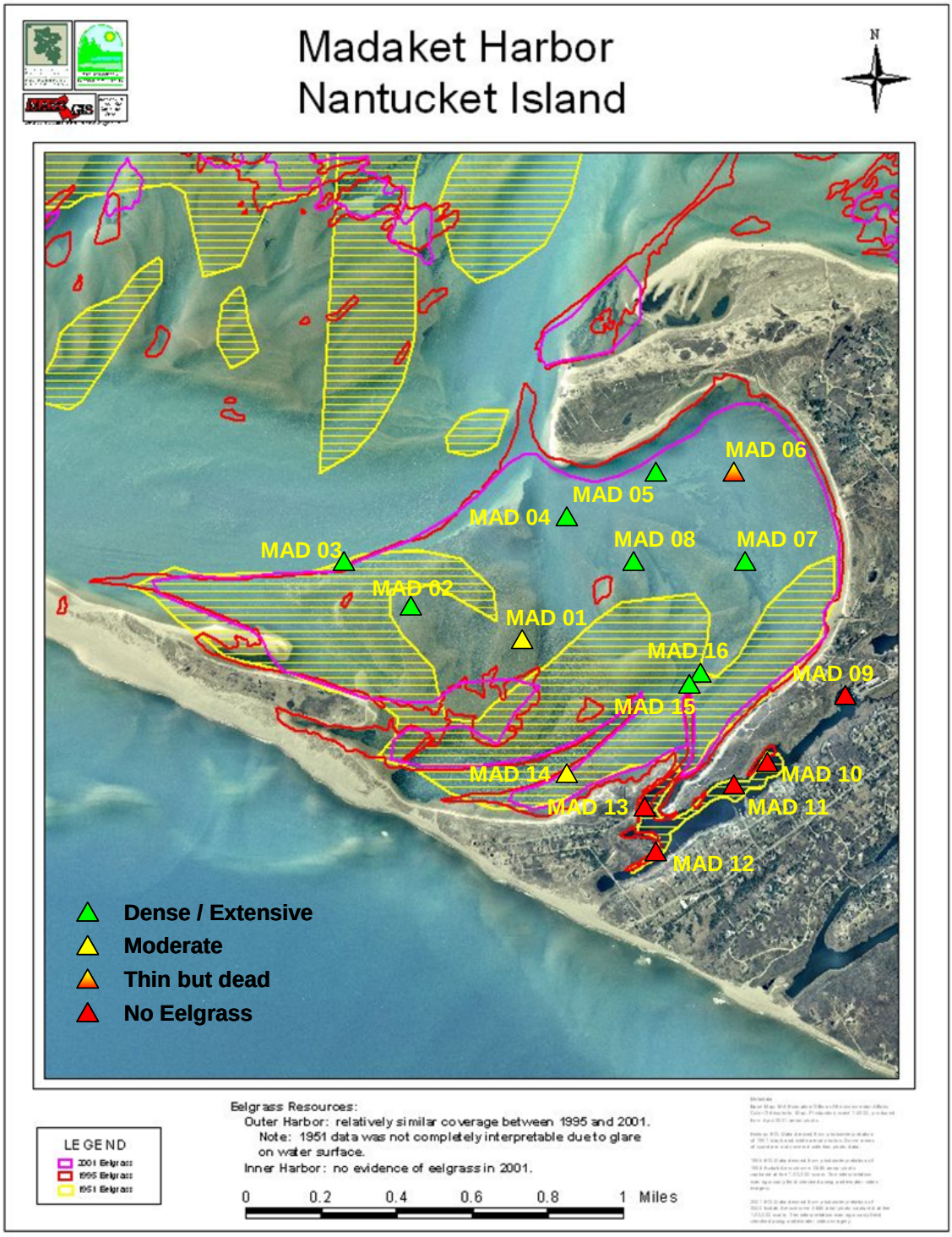

Figure VII-14. Map of eelgrass survey areas in Madaket Harbor as completed by the MassDEP Eelgrass Mapping Program with additional surveying of eelgrass presence and density completed by the SMAST-MEP Technical Team in 2003 (triangle symbols)

Table VII-3. Changes in eelgrass coverage in the Madaket Harbor Embayment System inclusive of Hither Creek within the Town Nantucket over the past half century (MassDEP, C. Costello).

Madaket Harbor Embayment System: Temporal Change in Eelgrass Coverage				
1951 acreage	1995 acreage	2001 acreage	2006 acreage	% Gain 1951 - 2006
377.73	673.33	604.75	605.16	38%

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 14 locations throughout the Madaket Harbor and Long Pond Embayment System (Figure VII-15 and VII-16), nine (9) within Madaket Harbor (inclusive of Hither Creek) and five (5) within Long Pond (inclusive of the North Head of Long Pond. In all cases multiple assays were conducted. In all areas and particularly those that do not support eelgrass beds such as Hither Creek and Long Pond, 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 recent loss of eelgrass beds in Hither Creek, it is clear that portions of the Madaket Harbor-Long Pond System are presently impaired by nitrogen enrichment. However, to the extent that these areas can still support healthy infaunal communities (and possibly a return of eelgrass through appropriate nutrient management), 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 (Chapter VIII).

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

The infaunal community survey indicated that a wide range of benthic animal habitat quality exists within the Madaket Harbor-Long Pond Embayment System. The highest quality infauna habitat was found throughout the main basin of Madaket Harbor, which also presently supports extensive eelgrass beds and sustains high oxygen levels and low chlorophyll levels, consistent with its low level of nitrogen enrichment. The Madaket Harbor main basin sediments presently support productive infauna communities with high numbers (660 individuals per sample), with high Evenness (0.72) and moderate to high diversity. The community is comprised of only a moderate number of species (8 on average) and while the community includes crustaceans and mollusks, it also includes some stress indicator species. This pattern

has been observed in other open basins that periodically have wash over, sand movement or high bottom water velocities. In contrast, Hither Creek has low numbers of individuals, species and diversity and is dominated by organic enrichment tolerant species (Capitellids). The upper reach of Hither Creek (between sites MAD 9 & 10) did not support any significant infaunal habitat, averaging only ~50 individuals per sample compared to 660 individuals in the main basin of the Harbor. The observed impaired infauna habitat is consistent with the observed oxygen and chlorophyll levels in this basin.

Figure VII-15. Aerial photograph of the Madaket Harbor system showing location of benthic infaunal sampling stations (yellow symbol).

Long Pond and North Head of Long Pond are brackish water basins with significant wetland influence. As such, these basins are naturally nutrient and organic matter enriched, and assessment of infaunal habitat considered their functional types. Overall, Long Pond and North Head of Long Pond presently support productive benthic animal communities. Long Pond shows high numbers of individuals, but with low numbers of species, diversity and Evenness. However, the species present are common to wetland channels throughout southeastern

Massachusetts and are dominated by a very common nutrient enrichment tolerant species, *Streblospio benedicti*, which is also common to pristine salt marsh creeks. However, the low numbers of total species and overall diversity indicate an impaired habitat consistent with the observed hypoxic conditions and elevated chlorophyll levels. The North Head of Long Pond is similar to Long Pond with lower numbers of individuals, but the community is dominated by amphipods rather than oligochaeta worms, indicative of a productive organic rich habitat and consistent with the observed oxygen levels in this basin.

Shellfish habitat within the Madaket Harbor - Long Pond Embayment System only occurs in the more marine basins of Madaket Harbor and Hither Creek. The brackish water basins of Long Pond and North Head of Long Pond have not been designated by MassDMF as suitable for shellfish growth (Figure VII-17).

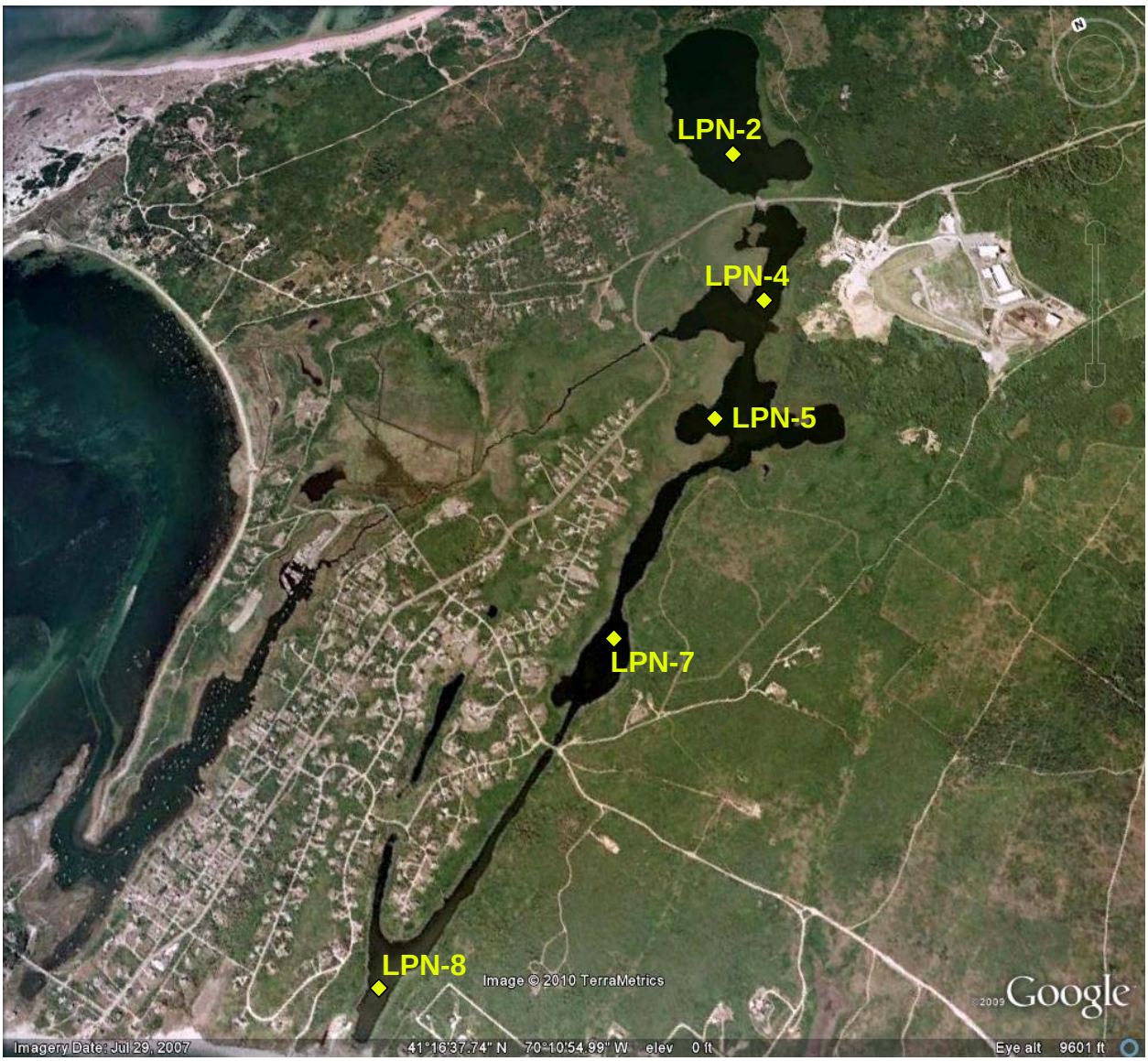

Figure VII-16. Aerial photograph of the Long Pond system showing location of benthic infaunal sampling stations (yellow symbol).

Table VII-4. Benthic infaunal community data for the Madaket Harbor - Long Pond Embayment System. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m^2). Stations refer to map in figure VII-17, S.E. is the standard error of the mean, N is the number of samples per site.

Basin	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)	Stations MAD & LPN[3]
Madaket Harbor - Long Pond Estuary						
Madaket Harbor			--[1]			
Mean =	8	666	8	2.23	0.72	MAD:3-5,7,14,15
S.E. =	1	145	1	0.29	0.07	
N =	6	6	6	6	6	
Hither Creek						
Mean =	4	123	5	1.36	0.69	MAD:9,11,12
S.E. =	1	82	1	0.46	0.17	
N =	3	3	3	3	3	
North Head Long Pond						
Mean =	5	181	5	1.59	0.68	LPN: 1
S.E. =	--	--	--	--	--	
N =	1	1	1	1	1	
Long Pond						
Mean =	5	947	6	1.19	0.60	LPN:4,5,7,8
S.E. =	2	583	1	0.47	0.10	
N =	4	4	4	4	4	

1- too few individuals extant in field sample to support this calculation.
2- all values are the average of replicate samples
3- MAD: Madaket Harbor, Hither Creek; LPN: Long Pond, North Head Long Pond, Fig.s VII-15, VII-16

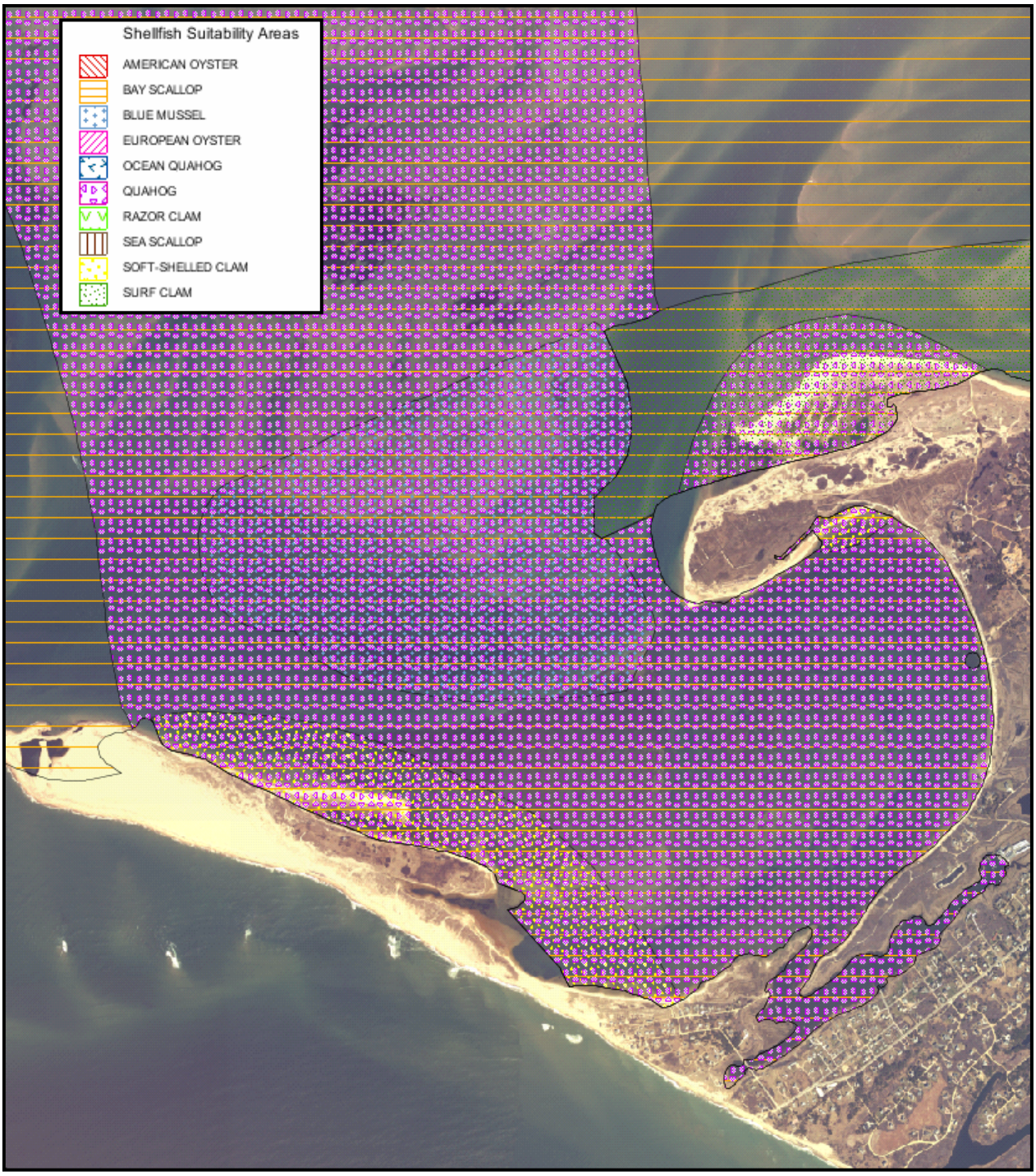

Figure VII-17. Location of shellfish suitability areas within the Madaket Harbor Estuary (inclusive of Hither Creek) as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence". Note that there are no shellfish suitability areas within Long Pond.

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll). Additional information on temporal changes within each sub-embayment of an estuary, its associated watershed nitrogen load and geomorphological considerations of basin depth, stratification and functional type (embayment, tidal river, wetland basin, salt marsh creek, etc.) further strengthen the analysis. These data were collected to support threshold development for the Madaket Harbor-Long Pond Embayment System by the MEP and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline Water Quality Monitoring Program conducted by the Nantucket Marine Department with technical and analytical support from the Coastal Systems Program at SMAST-UMass Dartmouth.

The Madaket Harbor-Long Pond Embayment System is a complex estuary with full tidal marine basins (Madaket Harbor, Hither Creek) connected via Madaket Ditch to tidally restricted brackish water basins (Long Pond, North Head Long Pond) that have significant wetland influence. The overall system is relatively shallow and vertically well mixed, the brackish basins are generally < 1m, although the northern basin (inlet to marina) of Hither Creek has been deepened by dredging (>2 m) and periodically has its vertical mixing reduced by salinity stratification increasing its sensitivity to nitrogen enrichment and oxygen depletion.

Each of type of functional component (salt marsh basin, embayment, tidal river, deep basin (sometimes drown kettles), shallow basin, etc.) has a different natural sensitivity to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of the specific type of basin and the ability to support eelgrass beds and the types of infaunal communities that they support. At present, some of the component basins within the Madaket Harbor-Long Pond Estuary are showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Chapter VII), indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

Overall, the large open water semi-enclosed main basin of Madaket Harbor is presently supporting high quality eelgrass habitat and productive benthic animal communities. Oxygen generally shows little depletion and chlorophyll a levels were consistently low. It is clear that the open nature of this basin and its relatively small watershed have resulted in only a low level of nitrogen enrichment and high quality habitat. In contrast, the enclosed basin of Hither Creek is presently nitrogen enriched, with high chlorophyll levels and periodic hypoxia (low oxygen). Habitat impairment is clear from the loss of previously existing eelgrass beds and the near absence of benthic animals in the upper reaches. The brackish basins of Long Pond and North Head of Long Pond are also nitrogen enriched beyond their assimilative capacity, but given the natural nutrient and organic matter enrichment of wetland influenced tidal basins their level of impairment is only moderate. There is no evidence that eelgrass habitat has existed previously in these basins, so the present absence does not indicate impairment of this habitat.

The decline in eelgrass within Hither Creek makes restoration of eelgrass the target for TMDL development by MassDEP and the primary focus of threshold development for this system. Additionally, restoration of the basins with impaired benthic animal habitat is also required. However, given the level of impairment in the brackish basins and the goal of restoring eelgrass in Hither Creek, it is certain that nitrogen management to restore eelgrass habitat within Hither Creek the will also result in restoration of the impaired infaunal habitat, as nitrogen enrichment will be significantly reduced to the overall estuary (Section VIII.3).

Eelgrass: At present, eelgrass coverage is extensive and stable throughout the main portion of Madaket Harbor. The 1951-2006 coverages (MassDEP Eelgrass Mapping Program) indicate a high quality eelgrass habitat, consistent with the oxygen and chlorophyll levels and the low level of nitrogen enrichment of Harbor waters (tidally averaged TN <0.33 mg L^{-1}). The existing beds have increased significantly relative to the estimate from 1951. Although from 1995 to 2006 there may have been a slight reduction in coverage, it is within the measurement error in this structurally dynamic system.

The temporal pattern of eelgrass coverage in Hither Creek clearly indicates that the eelgrass habitat within this basin is presently significantly impaired. In 1951, eelgrass beds covered much of the main basin of the Creek (to water quality station M11, Chapter VI). However, by 1995 the beds had been significantly reduced and limited to the margins of the basin and eelgrass was not found in the 2001 and 2006 MassDEP surveys or the MEP 2003 observations. Relative to recovery of this resource, the MEP Technical Team has determined that the marina at the head of Hither Creek was constructed between the 1951 and 1995 surveys and that the basin was deepened for navigation. However, deepening the basin does not explain the observed temporal loss of eelgrass, as the fringing beds and beds in the lower basin were observed in 1995, well after the deepening. The recent loss of the 1995 beds coupled with measured periodic hypoxia and high chlorophyll a levels supports the contention that nitrogen enrichment (tidally averaged TN of 0.51 mg L^{-1} at station M11 at the inland margin of the 1951 beds) caused the decline in eelgrass habitat. Deepening the basin does impact the ability to restore eelgrass in this basin to 1951 coverage, since the basin is now deeper and depositional. In its present basin configuration, restoration of the eelgrass habitat in Hither Creek, should focus on restoration of the fringing beds in the shallower margins of the basin to the inland extent of the 1951 coverage (water quality station, M11).

In contrast to Madaket Harbor and Hither Creek, the Long Pond basins do not appear to have eelgrass habitat, as there is not present or historical evidence of eelgrass within these basins. As a result eelgrass restoration within these brackish water basins cannot be justified as a nutrient management objective. However, the loss of eelgrass from Hither Creek from 1951-1995 and 1995 to 2001/2006, and the present absence of eelgrass from this basin, coupled to the present level of nitrogen enrichment, make restoration of this key estuarine resource a primary target for nitrogen management within the Madaket Harbor-Long Pond Embayment System.

Water Quality: The tidal waters of the Madaket Harbor-Long Pond Embayment System are currently listed under this Classification as SA. The enclosed component basins of Hither Creek, Long Pond and North Head of Long Pond are not presently meeting the water quality standards for SA waters. The result is that as required by the Clean Water Act, TMDL processes and management actions must be developed and implemented for the restoration of resources within this estuary. The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate only slightly nutrient enriched conditions within

Madaket Harbor and moderate to significant impairment of the enclosed component basins. However, the degree of enrichment and subsequent effect on habitat quality varied widely between these impaired sub-basins.

Madaket Harbor, which functions as a open marine basin generally has only moderate declines in oxygen, moderate amounts of phytoplankton biomass (chlorophyll a), and a low level of nitrogen enrichment (tidally averaged TN <0.33 mg L^{-1}), all factors consistent with its high quality eelgrass habitat. In contrast, Hither Creek's oxygen and chlorophyll a levels indicate a nitrogen and organic matter enriched basin with oxygen frequently declining below 4 mg L^{-1} and 3 mg L^{-1}, 45% and 25% of the time, respectively. Chlorophyll a levels were significantly elevated averaging 12 ug L^{-1} but were >10 ug L^{-1} 58% of the time, with blooms >20 ug L^{-1}. These elevated levels of phytoplankton are consistent with the observed periodic bottom water hypoxia and organic rich soft sediments of the basin. The periodic hypoxia, elevated chlorophyll levels (reduces light penetration), and sediment characteristics are consistent with a nitrogen enriched basin with significantly impaired eelgrass habitat. The oxygen and chlorophyll a data further support the conclusion that Hither Creek habitats are likely presently impaired by nitrogen enrichment.

Long Pond is a tidally restricted brackish pond dominated by fringing wetlands. Oxygen depletion is large and frequent, generally following the diurnal light/dark cycle. Oxygen frequently declined to <2 mg L^{-1}, with a large daily excursion frequently rising to 2-3 times air equilibration. Although natural wetland channels periodically are hypoxic/anoxic at night, the large daily oxygen excursions are atypical and indicate impairment. Consistent with the oxygen levels, chlorophyll a levels were very high, averaging 43 ug L^{-1} with blooms exceeding 80 ug L^{-1} (Table VII-2). The Nantucket Water Quality Monitoring Program observed similarly high chlorophyll a levels, averaging 25 ug L^{-1} over the multiyear program. The oxygen and chlorophyll a data indicate that while the middle portion of Long Pond is a wetland dominated basin and therefore naturally nutrient and organic matter enriched, the large phytoplankton blooms coupled with the large oxygen excursions suggest that it is currently beyond its nutrient assimilative capacity. The southern tidal reach of Long Pond is less nutrient enriched and shows a lower degree of habitat impairment. Oxygen levels reflect the nutrient and organic rich nature of this system, but without the prolonged hypoxia, large daily excursions and very large phytoplankton blooms found within the mid basin. Oxygen levels were typically <6 mg L-1 (63% of time), with periodic declines below 4 mg L^{-1} and 3 mg L^{-1}. Daytime levels rarely exceeded 1.5 times air equilibration, reflecting the moderate chlorophyll a levels, which averaged 15.9 ug L-1 and rarely exceeded 25 ug L-1. While these levels are elevated, they are ~1/3 lower than found in the mid basin. While Long Pond, overall, has significant wetland influence and therefore is naturally enriched in nutrients and organic matter the chlorophyll a and to a lesser extent oxygen records indicate that this lower basin is also beyond its nutrient assimilative capacity.

Overall, the oxygen and chlorophyll a levels within the Madaket Harbor - Long Pond System indicate little to no impairment of the outer harbor consistent with its low level of nitrogen enrichment. In contrast, Hither Creek which receives high quality waters on the flooding tide from Madaket Harbor, but nutrient and organic matter enrichment from its watershed inputs and from the upper estuarine reaches via Madaket Ditch, has oxygen declines and chlorophyll levels consistent with its tidally averaged TN of 0.51 mg L^{-1} (Chapter VI), indicating nitrogen related habitat impairment. Long Pond and North Head of Long Pond are brackish wetland influenced systems that are naturally enriched with nutrients and organic matter. The North Head of Long Pond supported generally high oxygen conditions and moderate chlorophyll a levels at a high tidally averaged TN (0.89 mg L^{-1}). Based upon the

function type of this basin, the oxygen and chlorophyll a levels are indicative of high quality to possibly slightly impaired habitat. In contrast, the wetland dominated Long Pond basin is presently showing wide oxygen excursions, frequent hypoxia/anoxia and very high chlorophyll levels indicating that even this naturally enriched system is receiving external nitrogen loading that is resulting in habitat impairments. Tidally averaged TN levels throughout this basin range from 0.85 mg TN L^{-1} to 1.0 mg TN L^{-1}.

Infaunal Communities: In all areas and particularly those that do not support eelgrass beds, benthic animal indicators are 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 survey of infauna communities throughout the Madaket Harbor-Long Pond Estuary indicated a system presently supporting impaired benthic infaunal habitat in its enclosed component sub-basins (Hither Creek, Long Pond, North Head of Long Pond).

A wide range of benthic animal habitat quality exists within the Madaket Harbor-Long Pond Embayment System. The highest quality infauna habitat was found throughout the main basin of Madaket Harbor that also presently supports extensive eelgrass beds and sustains high oxygen levels and low chlorophyll levels, consistent with its low level of nitrogen enrichment. The Madaket Harbor main basin sediments presently support productive infauna communities with high numbers (660 individuals per sample), with high Evenness (0.72) and moderate to high diversity. The community is comprised of only a moderate number of species (8 on average), while the community includes crustaceans and mollusks, it also includes some stress indicator species. This pattern has been observed in other open basins that periodically have wash-over event, sand movement or high bottom water velocities. In contrast, Hither Creek has low numbers of individuals, species and diversity and is dominated by organic enrichment tolerant species (Capitellids). The upper reach of Hither Creek (between water quality monitoring sites MAD 9 & 10) did not support any significant infaunal habitat, averaging only ~50 individuals per sample. The observed impaired infauna habitat is consistent with the observed oxygen and chlorophyll levels in this basin. Long Pond and North Head of Long Pond are brackish water basins with significant wetland influence. As such, these basins are naturally nutrient and organic matter enriched, and assessment of infaunal habitat accounted for their functional types. Overall, these brackish basins presently support productive benthic animal communities. Long Pond supports high numbers of individuals, but low species numbers, diversity and Evenness. The species are typical of wetland channels, with the dominant species, *Streblospio benedicti*, a very common nutrient enrichment tolerant species. However, the low numbers of total species and overall diversity indicate an impaired habitat consistent with the observed hypoxic conditions and elevated chlorophyll levels. The North Head of Long Pond is similar to Long Pond with lower numbers of individuals, but the community is dominated by amphipods rather than oligochaeta worms, indicative of a productive organic rich habitat and consistent with the observed oxygen levels in this basin. Management of nitrogen levels through reduction in watershed nitrogen inputs or increased tidal flushing, as appropriate, is required for restoration of eelgrass and infaunal habitats within the Madaket Harbor-Long Pond Embayment System.

Table VIII-1. Summary of nutrient related habitat quality within the Madaket Harbor - Long Pond Estuary within the Town of Nantucket, MA, based upon assessments in Section VII. Long Pond and North Head of Long Pond were assessed as naturally nutrient and organic matter enriched wetland dominated shallow basins. NWQMP: Nantucket Water Quality Monitoring Program.

Health Indicator	Madaket Harbor - Long Pond Embayment System				
	Madaket Harbor	Hither Creek	Long Pond		North Head Long Pond
			Mid	Lower	
Dissolved Oxygen	H[1]	SI[2]	MI-SI[3]	MI[4]	H[5]
Chlorophyll	H[6]	MI/SI[7]	SI[8]	MI/SI[9]	H/MI[10]
Macroalgae	H[11]	SI[12]	--[13]	--[13]	--[14]
Eelgrass	H[15]	SI[16]	--[17]	--[17]	--[17]
Infaunal Animals	H[18]	SI[19]	MI[20]	MI[20]	H-MI[21]
Overall:	**H[22]**	**SI[23]**	**MI[24]**		**H/MI[25]**

1- oxygen levels almost always > 5mg/L (95% of time), above 6 mg/L (80% of time), with modest diurnal shifts, NWQMP data suggests that oxygen was generally >6 mg/L, with the minimum level recorded in the outer basin, 5.9 mg/L and in the inner basin areas, 5.2 mg/L.
2- oxygen levels frequently below 4 mg/L and 3 mg/L, 45% and 25% of the time, respectively but infrequently below 2 mg/L, NWQMP minimums were 3.3-4.0 mg/L.
3- oxygen levels <4 mg/L, 31% of record, with frequent declines to <2 mg/L, although wetland dominated the large daily excursions (3 times air equilibration) indicate impairment. The level of impairment is less than for an open water basin, due to the significant wetland influence.
4- periodic hypoxia/anoxia with declines below 4 mg/L and 3 mg/L (16% and 11% of time), <6 mg/L 63% of time, daily excursion modest; impairment is less than for open water basins, due to wetland influences.
5- generally >6 mg/L, with rare depletions below 5 mg/L not indicative of nutrient impairment.
6- levels low for a coastal basin, averaging 5.2 ug/L (mooring) and always <14 ug/L, <5 ug/L 64% of the time. NWQMP levels low, averaging 3.3 ug/L - 5.3 ug/L.
7- levels significantly elevated over Madaket Harbor, average 12 ug/L, >10 ug/L 58%of the time, with blooms >20 ug/L, NWQMP averaged 7.7 - 9.4 ug/L within the Creek basin.
8- levels high for a wetland dominated basin, mooring average 43 ug/L, NWQP 25 ug/L.
9- moderately elevated for a wetland basin, averaging 15.9 ug/L infrequently >25 ug L-1.
10- low to moderate levels for a wetland basin, generally 5-10 ug/L, average 8 ug/L, NWQMP average 10 ug/L
11- drift algae sparse or absent, some patches of attached Codium
12- areas of dense drift algae, Ulva, with some filamentous species, primarily in upper basin.
13- very sparse drift algae, but areas of rooted submerged aquatic vegetation (SAV)
14- no drift algae observed.
15- MassDEP (C. Costello) indicates high eelgrass coverage from 1951-2006.
16- eelgrass decline from 1951 to 1995, remaining eelgrass lost by 2001/ 2006.
17- no evidence this basin is supportive of eelgrass.
18- high numbers of individuals and Evenness, moderate species numbers and diversity community includes crustaceans and mollusks
19- low numbers of individuals, species and diversity; dominated by organic enrichment species (Capitellids), upper reach does not support any significant infaunal habitat,
20- high numbers of individuals, but low numbers of species, diversity & Evenness, community comprised of species common to wetland channels & dominated Streblospio benedicti,
21- moderate numbers of individuals, low species numbers, dominance by amphipods indicative of moderate l organic enrichment, in this wetland influenced basin.
22- High quality estuarine habitat, with little oxygen depletion, low chlorophyll, stable eelgrass habitat and productive benthic animal communities.
23- Significant Impairment based upon loss of eelgrass from system, 1951-1995 & impaired benthic animal habitat, and hypoxia and dense accumulations of drift algae in upper basin.
24- Moderate Impairment based upon the elevated chlorophyll and infaunal community structure
25- High quality to moderately impaired based primarily on infaunal community structure and moderately elevated chlorophyll levels.

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 that will support acceptable habitat quality throughout an embayment system is to first identify a sentinel location within the embayment and secondly, to determine the nitrogen concentration within the water column that will restore the location to the desired habitat quality. The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined (Section VIII.2), the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved (Section VIII.3.

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Madaket Harbor-Long Pond Embayment System is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. Given the information on a variety of key habitat characteristics, it is possible to develop a site-specific threshold, which is a refinement upon more generalized threshold analyses frequently employed. Each of type of functional component (salt marsh basin, embayment, tidal river, deep basin (sometimes drown kettles), shallow basin, etc.) has a different natural sensitivity to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of the specific type of basin and the ability to support eelgrass beds and the types of infaunal communities that they support. At present, some of the component basins within the Madaket Harbor-Long Pond Estuary are showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Chapter VII), indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

Overall, the large open water semi-enclosed main basin of Madaket Harbor is presently supporting high quality eelgrass habitat and productive benthic animal communities. Oxygen generally shows little depletion and chlorophyll a levels were consistently low, with only very sparse macroalgal abundance. In contrast, the enclosed basin of Hither Creek is presently nitrogen enriched with a tidally averaged TN of 0.51 mg N L^{-1} compared to 0.33 mg N L-1 in Madaket Harbor. The result is high chlorophyll levels and periodic hypoxia (low oxygen), complete loss of eelgrass habitat and regions of dense accumulations of drift macroalgae. In addition, the benthic animal habitat is impaired and nearly absent in much of the northern tidal basin. While nitrogen management needs to target eelgrass restoration in this basin, it will also restore benthic animal habitat, as benthic communities are generally more tolerant of nitrogen enrichment effects than is eelgrass.

The brackish basins of Long Pond and North Head of Long Pond are also nitrogen enriched beyond their assimilative capacity, but given the natural nutrient and organic matter enrichment of wetland influenced tidal basins their level of impairment is only moderate. TN levels are elevated in these basins, 0.85 - 1.05 mg N L-1, typical of wetland basins and tidal creeks. However, some impairment of habitat presently exists, seen primarily in the high chlorophyll levels and periodic blooms and structure of the benthic animal community. There is no evidence that eelgrass habitat has existed previously in these basins, so the present absence does not indicate impairment of this habitat.

The decline in eelgrass within Hither Creek makes restoration of eelgrass the target for TMDL development by MassDEP and the primary focus of threshold development for this system. Additionally, restoration of the basins with impaired benthic animal habitat is also

required. However, given the level of impairment in the brackish basins and the goal of restoring eelgrass in Hither Creek, it is certain that nitrogen management to restore eelgrass habitat within Hither Creek the will also result in restoration of the impaired infaunal habitat, as nitrogen enrichment will be significantly reduced to the overall estuary. As such, it appears that the appropriate sentinel station for the Madaket Harbor-Long Pond Embayment System should be located at the northern most extent of the 1951 eelgrass coverage in Hither Creek, which coincides with the baseline Nantucket Water Quality Monitoring Station, M11. Analysis of the "new" bathymetry associated with this sub-basin, indicates that when the basin had full eelgrass coverage, the depth was shallower than the present 2+ meters. The present depth makes restoration of eelgrass to the 1951 coverage in Hither Creek unlikely. However, restoration of the fringing beds that existed in 1951 and 1995 should be the management target. This will require lowering the present level of nitrogen enrichment in this basin, which should also restore the benthic animal habitat and eelgrass seaward of the sentinel station. Secondarily, the benthic animal habitats in the upper brackish basins of Long Pond and North Head of Long Pond are also moderately impaired by nitrogen. However, reduction of nitrogen loading to these systems is part of nitrogen management required to lower nitrogen levels at the sentinel station, since the upper pond basins discharge their nitrogen to Hither Creek via Madaket Ditch.

To achieve the restoration target of restoring the fringing eelgrass beds in Hither Creek requires lowering the level of nitrogen enrichment. Within Madaket Harbor the basin-wide tidally averaged TN is presently <0.33 mg N L-1, and the basin is supporting high quality eelgrass and benthic infaunal habitat. However, Madaket Harbor eelgrass coverage includes areas in deeper water than that of the location of the fringing eelgrass beds to be restored in Hither Creek (< 1 m) and so a higher level of nitrogen is appropriate for restoration in Hither Creek.

In shallow systems like the restoration area in Hither Creek, eelgrass beds are sustainable at higher TN (higher chlorophyll a) levels than in deeper waters, because of the "thinner" watercolumn that light has to pass through to support eelgrass growth (less water to penetrate). The observed loss of eelgrass in Hither Creek is similar to that in Farm Pond on Martha's Vineyard where declining eelgrass heavy with epiphytes was observed at the same tidally averaged TN of 0.51 mg L^{-1}. Farm Pond is a shallow water basin with depths generally less than 1 meter. In other systems analogous to the restoration location in Hither Creek, for example at similar depths in Bournes Pond, eelgrass can be still be found (although heavy with epiphytes) at the mouth of the upper tributary at a tidally averaged TN concentration of 0.481 mg TN L^{-1}, while the more stable beds in the lower region of Israel's Cove have at a tidally averaged TN of 0.429 mg TN L^{-1}. Similarly, areas non-supportive of healthy beds also have higher TN levels. Eelgrass within Hamblin Pond persisted at a TN level of 0.5 mg L-1, but diminished to a few small patches. Therefore to restore eelgrass habitat in Hither Creek the nitrogen concentration (tidally averaged TN) at the sentinel location needs to be between 0.48 and 0.43 mg TN L^{-1}. A threshold of 0.45 mg TN L^{-1} was determined to be appropriate for the Hither Creek sentinel station to restore eelgrass (and infaunal habitat) within this basin. This threshold level is consistent with high quality shallow water habitat in Bournes Pond and is similar to eelgrass within the Parker's River, tidally averaged TN level (0.45 mg TN L^{-1}). This represents a relatively high threshold as a result of the shallow depth of the entirety of the potential eelgrass habitat. The goal is to achieve the nitrogen target at the sentinel location and restore eelgrass habitat, that will also result in the restoration of infaunal habitat throughout the System. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal stations are discussed in Section VIII.3, below. However, it should be noted that as the benthic habitats in the brackish systems are naturally nitrogen enriched, a moderate reduction in nitrogen levels should be sufficient to restore the benthic habitat. In tidal

wetlands the nitrogen levels between 1 and 2 mg N L^{-1} are associated with unimpaired habitat. This is consistent with the only slight impairment of the North Head of Long Pond at TN levels of 0.894 mg L^{-1} and the moderately impaired benthic habitat in Long Pond at an basin averaged TN (tidally averaged) of 0.939 mg N L^{-1}. Given the observed level of impairment in these brackish basins and the frequent association of high quality benthic habitat in wetland influenced tidal channels at 1 mg N L-1, a threshold of 0.8 mg N L-1 is appropriate as the average basin TN level to be supportive of benthic animal habitat. This is a secondary threshold and one that should be met as nitrogen management options are implemented to meet the nitrogen threshold at the down-gradient sentinel station. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations are discussed in Section VIII.3, below.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Madaket Harbor system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, first by removing the landfill load from Long Pond (which represents 66% of the watershed load), and then using reductions in septic effluent discharges, until the nitrogen levels reached the threshold level at the sentinel station chosen for Hither Creek. It is important to note that load reductions can be produced by reduction of any or all sources. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment. A comparison between present septic and total watershed loading and the loadings for the two modeled threshold scenarios is provided in Tables VIII-2 and VIII-3.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required 56% 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 100% of the septic load from the Hither Creek watershed results in a 72% reduction in total watershed nitrogen load. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent ‘worst-case’ summertime conditions.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-4. To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN concentrations of 12% are required in the system.

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

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

sub-embayment	present septic load (kg/day)	threshold septic load (kg/day)	threshold septic load % change
Madaket Harbor	0.384	0.384	0.0%
Hither Creek	2.907	0.000	-100.0%
Madaket Ditch	1.510	1.510	0.0%
North Head Long Pond	0.071	0.071	0.0%
Long Pond	0.342	0.342	0.0%
System Total	5.214	2.307	-55.8%

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Madaket Harbor	0.663	0.663	0.0%
Hither Creek	4.041	1.134	-71.9%
Madaket Ditch	2.433	2.433	0.0%
North Head Long Pond	0.238	0.238	0.0%
Long Pond	3.230	1.101	-65.9%
TOTAL – Madaket Harbor System	10.605	5.570	-47.5%

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Madaket Harbor	0.663	8.603	17.952
Hither Creek	1.134	0.534	-0.583
Madaket Ditch	2.433	-	0.061
North Head Long Pond	0.238	0.975	3.065
Long Pond	1.101	0.693	0.995
TOTAL – Madaket Harbor System	5.570	10.805	21.49

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the Madaket Harbor System. The threshold stations are in bold print (0.45 mg/L for M11).

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Madaket Harbor	M1	0.3107	0.3095	-0.4%
Madaket Harbor	M2	0.3205	0.3180	-0.8%
Madaket Harbor	M3	0.3280	0.3237	-1.3%
Hither Creek	M4	0.4639	0.4170	-10.1%
Hither Creek	M5	0.6130	0.5337	-12.9%
Madaket Harbor	M6	0.3161	0.3141	-0.6%
Madaket Harbor	M10	0.3266	0.3227	-1.2%
Hither Creek	**M11**	**0.5107**	**0.4500**	**-11.9%**
Long Pond	LOPO1	1.0394	0.8460	-18.6%
Long Pond	LOPO2	0.9827	0.8050	-18.1%
Long Pond	LOPO3	0.8821	0.7380	-16.3%
Long Pond	LOPO4	0.8515	0.7174	-15.7%
North Head Long Pond	LOPO5	0.8937	0.7654	-14.4%

Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Madaket Harbor estuary, for threshold conditions. Threshold station is shown (0.45 mg/L at M11 in Hither Creek).

IX. LANDFILL IMPACTS TO WATER QUALITY

The Town of Nantucket presently operates a landfill adjacent the upper reach of Long Pond. The landfill has been in operation for a number of decades. The Town has begun an intensive process to mine the accumulated landfill deposits and has finished the first year of a five year process that is reducing the land fill contribution to the nitrogen load of Long Pond from the current unlined landfill. Material in the current unlined landfill is being removed, sorted, and portions are being passed through a digester and/or recycled (personal communication, Jeff Willett, Director, Department of Public Works). Any materials remaining after this recovery process are placed in lined cells that are being constructed on the site. As these cells fill, they will be capped to prevent contamination of groundwater, thereby reducing the nitrogen load from the landfill. Current plans call for a re-evaluation of the landfill status in five years. At that time, evaluation of these efforts may lead to capping of the smaller old landfill area that remains. Nitrogen loads from the landfill site will be reduced by activities completed during the present 5 year phase, and will likely be eliminated if the landfill is capped in the future.

To assess the response of Long Pond to reductions in the present nitrogen emanating from the unlined landfill and to reflect the new course that the Town of Nantucket has undertaken, the MEP conducted a scenario run of the calibrated and validated Linked Watershed-Embayment Model for the Madaket Harbor - Long Pond Estuary. In this scenario, the present nitrogen load from the landfill was removed, with all other existing loads remaining unchanged. These results were compared to the Existing Conditions described in Chapter VI.

As an alternative to the solution presented in Section VIII.3, a scenario was run with the landfill load discussed above completely removed from the Long Pond watershed. The presentation is to establish the general degree and spatial pattern of reduction that will be achieved by this alternative for restoration of this nitrogen impaired embayment. Present septic and total watershed loading and the loadings for the modeled threshold scenarios is provided in Tables IX-1 and IX-2 for the readers convenience in order to make a comparison to the landfill alternative analyzed.

As shown in Table IX-1, there is no change in septic loading for this scenario. This is done to examine the impact of the landfill on the entire system. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure IX-1.

Tables IX-2 and IX-3 provide additional loading information associated with the alternative analysis. Table IX-2 shows the change to the total watershed loads, based upon the removal of the landfill. Removal of the landfill from the Long Pond watershed results in a 20% reduction in total watershed nitrogen load for the entire system. Table IX-3 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table IX-3, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent ‘worst-case’ summertime conditions.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table IX-3. To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN concentrations of 12% is required in the system (Section VII.3). The alternative shown here results in a reduction in TN concentrations of 5%, with TN concentrations at the sentinel station of 0.485 mg/L. Therefore, removal of the landfill load alone is not sufficient to reach the nitrogen

threshold level of 0.45 mg/L at station M11(Table IX-4). Additional load reductions will be required, likely through further reductions in septic loading.

Table IX-1. Comparison of sub-embayment watershed septic loads (attenuated) used for modeling of present and no-landfill loading scenarios of the Madaket Harbor System. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.

sub-embayment	present septic load (kg/day)	scenario septic load (kg/day)	scenario septic load % change
Madaket Harbor	0.384	0.384	0.0%
Hither Creek	2.907	2.907	0.0%
Madaket Ditch	1.510	1.510	0.0%
North Head Long Pond	0.071	0.071	0.0%
Long Pond	0.342	0.342	0.0%
System Total	5.214	5.214	0.0%

Table IX-2. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and no-landfill loading scenarios of the Madaket Harbor System. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	scenario % change
Madaket Harbor	0.663	0.663	0.0%
Hither Creek	4.041	4.041	0.0%
Madaket Ditch	2.433	2.433	0.0%
North Head Long Pond	0.238	0.238	0.0%
Long Pond	3.230	1.101	-65.9%
TOTAL – Madaket Harbor System	10.605	8.479	-20.1%

Table IX-3. Threshold sub-embayment loads used for total nitrogen modeling of the Madaket Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Madaket Harbor	0.663	8.603	17.952
Hither Creek	4.041	0.534	-0.583
Madaket Ditch	2.433	-	0.061
North Head Long Pond	0.238	0.975	3.065
Long Pond	1.101	0.693	0.995
TOTAL – Madaket Harbor System	8.479	10.805	21.49

Table IX-4. Comparison of model average total N concentrations from present loading and the no-landfill scenario, with percent change, for the Madaket Harbor System. The threshold stations are in bold print (where the target threshold is 0.45 mg/L for M11).

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Madaket Harbor	M1	0.3107	0.3102	-0.2%
Madaket Harbor	M2	0.3205	0.3194	-0.3%
Madaket Harbor	M3	0.3280	0.3262	-0.5%
Hither Creek	M4	0.4639	0.4443	-4.2%
Hither Creek	M5	0.6130	0.5683	-7.3%
Madaket Harbor	M6	0.3161	0.3153	-0.3%
Madaket Harbor	M10	0.3266	0.3250	-0.5%
Hither Creek	**M11**	**0.5107**	**0.4847**	**-5.1%**
Long Pond	LOPO1	1.0394	0.8792	-15.4%
Long Pond	LOPO2	0.9827	0.8384	-14.7%
Long Pond	LOPO3	0.8821	0.7717	-12.5%
Long Pond	LOPO4	0.8515	0.7512	-11.8%
North Head Long Pond	LOPO5	0.8937	0.7979	-10.7%

Figure IX-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Madaket Harbor estuary, for scenario conditions. Threshold station is shown (where the target threshold is 0.45 mg/L at M11 in Hither Creek).

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