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Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Madaket Harbor and Long Pond Nantucket, Massachusetts

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.