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Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Nantucket Harbor 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 Nantucket Harbor embayment system, a coastal embayment of the Island of Nantucket within the Town of Nantucket, Massachusetts. Analyses of the Nantucket Harbor 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 Nantucket Harbor embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Town) for the restoration of the Nantucket Harbor embayment system.

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

The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the

culture, economy, and tax base of Massachusetts's coastal communities. The primary nutrient causing the increasing impairment of our coastal embayments is nitrogen, with its primary sources being wastewater disposal, and nonpoint source runoff that carries nitrogen (e.g. fertilizers) from a range of other sources. Nitrogen related water quality decline represents one of the most serious threats to the ecological health of the nearshore coastal waters. Coastal embayments, because of their shallow nature and large shoreline area, are generally the first coastal systems to show the effect of nutrient pollution from terrestrial sources.

In particular, the Nantucket Harbor 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. Nantucket 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 sustain a scallop fishery. 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.state.ma.us/dep/smerp/smerp.htm>. A more basic discussion of the Linked Model is also provided in Appendix F of the *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at <http://www.state.ma.us/dep/smerp/smerp.htm>. The Linked Model suggests which management solutions will adequately protect or restore embayment water quality by enabling towns to test specific management scenarios and weigh the resulting water quality impact against the cost of that approach. In addition to the management scenarios modeled for this report, the Linked Model can be used to evaluate additional management scenarios and may be

updated to reflect future changes in land-use within an embayment watershed or changing embayment characteristics. In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries. Unlike many approaches, the Linked Model accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics and accommodates the spatial distribution of these processes. For an overview of several management scenarios that may be employed to restore embayment water quality, see *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at <http://www.state.ma.us/dep/smerp/smerp.htm>.

Application of MEP Approach: The Linked Model was applied to the Nantucket Harbor 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 Nantucket 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 land-use data obtained from the Town was used to determine watershed nitrogen loads within the Nantucket 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 Nantucket Harbor embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model 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 Nantucket Harbor 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 Nantucket Harbor system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel station chosen for the Nantucket 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 Nantucket Harbor 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 28% - 53% of the controllable watershed load to the Nantucket 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.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Nantucket Harbor system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. At present, the Nantucket Harbor System is showing variations in nitrogen enrichment among its 4 principal component basins. The inner basins of Head of the Harbor and Polpis Harbor are nitrogen

enriched over Quaise and the Town basins. Although the component basins of the Nantucket Harbor System are clearly enriched in nitrogen over the adjacent Nantucket Sound waters, the enrichment is relatively small, generally $<0.100 \text{ mg L}^{-1}$ (see Chapter VI).

The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally $\sim 7\text{-}8 \text{ mg L}^{-1}$ at the mooring sites). Overall, oxygen within the Harbor bottom waters appears to remain at ecologically healthy levels, except for periodic oxygen depletion within the deepest portions of the Quaise and Wauwinet basins. However, as there were some oxygen depletions below 5 mg L^{-1} in the main basins (although infrequent), it appears that the system is at or just beyond its ability to assimilate additional nitrogen/organic matter.

Within the highly flushed and generally well mixed waters of the lower basins of Nantucket Harbor, bottom waters were well oxygenated ($>6 \text{ mg L}^{-1}$). The few excursions below 6 mg L^{-1} were isolated events, rather than a prolonged depletion such as generally associated with a phytoplankton bloom. However, these variations were small and overall the oxygen conditions are consistent with the observations of healthy infaunal and eelgrass communities. While Polpis Harbor also exhibited well oxygenated conditions, larger diurnal variations were recorded than in the outer basins. The higher diurnal fluctuations indicate waters supporting higher phytoplankton biomass. Quaise basin showed both significant diurnal oxygen fluctuations and an overall oxygen decline, although not to levels of high stress. There was a single "event" of a few days when each night oxygen levels reached 4 mg/L , but returned to $\sim 5 \text{ mg L}^{-1}$ each following day. Since the meter was located deeper within the basin ($\sim 6 \text{ m}$), oxygen levels throughout most of the basin area were almost certainly higher given their shallower depths, only in the "deep hole" was oxygen depletion likely greater. Assessing oxygen conditions within the Quaise basin indicates generally non-stressful oxygen levels, except for the deep basin. However, it is likely that the presence of the deep hole ($\sim 30'$) creates a geomorphological (natural) cause of the low dissolved oxygen. Head of the Harbor showed generally high oxygen levels. As in the Quaise basin, the meter was deeper in the basin and observed oxygen depletions were greater than experienced by bottom waters throughout most of the basin area. The oxygen conditions are consistent with the observed distribution of habitat quality throughout the Harbor System, with the deep waters showing oxygen depletion, but with oxygen levels generally supportive of a high habitat quality for infauna. However, since the system does show oxygen levels less than full atmospheric saturation, additional organic matter loads, (e.g. through nitrogen inputs) will likely increase the magnitude and frequency of the oxygen declines, again indicating a system at or just beyond its nitrogen assimilative capacity (nitrogen threshold).

Based upon all available data it appears that eelgrass is presently a widespread critical habitat within the Nantucket Harbor System. The present distribution of eelgrass results from recolonization of the Harbor from its loss in the 1930's. A map of eelgrass from the 1940's "shows it to be primarily confined to parts of the Jetties and Horse shed at the Harbor entrance (Kelley 1989). Kelley (1989) concluded that from the 1960's to 1989, "eelgrass distribution has been relatively stable in Nantucket Harbor...". However, it is clear that eelgrass beds have been lost from this System. Both the MassDEP analysis and the direct observations of Kelley in 1989 indicated that there has been measurable eelgrass loss. The primary locations are within Head of the Harbor and East Polpis Harbor. The other major region experiencing gradual losses, the marginal areas of Head of the Harbor, is supported by both Kelley (1989) and the MassDEP survey data. This larger areal loss appears to be gradual and occurring primarily in the least well flushed areas of this basin (note the counterclockwise circulation). Eelgrass loss has also been noted to the west of Pocomo, which was observed in the 1980 surveys and more recently

in changes from 1995-2001. It is important to note that the eelgrass bed loss is both from the shallow area of the upper and mid regions of Head of the Harbor (<8' depth) and from the "deeper" areas (8'-12') in the lower reach and from the shallow east basin of Polpis. The data indicate that that on the order of 1000 acres of eelgrass habitat within the Nantucket Harbor System is impaired.

It is important to note that the nitrogen levels throughout the Nantucket Harbor System remain relatively low, consistent with the observed oxygen conditions, lack of macroalgae and chlorophyll a levels. However, due to the water depth in the Harbor, it is possible that vertical and horizontal mixing rates appear to have resulted in a decline in eelgrass bed coverage from the deeper areas and more enclosed basin areas.

Macro-algal abundance within the Harbor surveyed in 1994 (Harbor Study 1997) was typical of a relatively healthy environment. Algal cover was highest on the Nantucket Sound side between the points of Coatue (Figure VII-10). The highest concentrations of macro-algae were consistent with the circulation patterns associated with the cusps of land present around the Harbor edge. It also appears that the macro-algal accumulations are not related to terrestrial nitrogen inputs, since the "island" side of the Harbor, which dominates the land based loadings, had lower algal accumulations than Coatue. The absence of macroalgal accumulations and drift algae is consistent with the generally low nitrogen levels throughout this System and the relatively low watershed nitrogen input.

The infaunal data clearly show that the lower basins and shallower areas (<12') of the main Harbor basins generally support high quality infaunal habitat. The lowermost basin (Town) exhibited a dense, highly diverse and relatively evenly distributed community, with some variation. The shallower margins of both Quaise and Head of the Harbor were only slightly less diverse than areas nearer the tidal inlet, but were clearly of high quality. This is further evidenced by the growth of epibenthic scallops in these areas. Within the main Harbor basins, only the deep "holes" showed reduced numbers of species and individuals and organic enrichment indicators. This indication of moderate to poor habitat in these deep regions is consistent with previous analyses and supported by the observed accumulations of organic detritus in these natural depositional areas. It is unlikely that management of nitrogen loading will be able to create significant improvement within these deep basin regions and it is likely that these areas have been "stressed" by natural processes for a long time.

Overall, the MEP system-wide infaunal survey found higher numbers of species and individuals in communities that were generally more diverse and evenly distributed than the other 20 embayments examined to date by the MEP in southeastern Massachusetts. This is consistent with the relatively low tidally averaged nitrogen levels within the system, <0.40 mg N L⁻¹ and generally 0.285-0.361 mg N L⁻¹.

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, Nantucket Harbor embayment system was comprised primarily of runoff from impervious surfaces, fertilizers and wastewater nitrogen. Land-use and wastewater analysis found that generally about 28% - 53% of the controllable watershed nitrogen load to the embayment was from wastewater.

A major finding of the MEP clearly indicates that a single total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of the Great, Green and Bourne Pond Systems, Popponesset Bay System, the Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay, the analysis of the adjacent Rushy Marsh system and the Pleasant Bay and Nantucket Sound embayments associated with the Town of Chatham. This is almost certainly going to be true for the other embayments within the MEP area, as well.

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

Nantucket Harbor Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Nantucket Harbor 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 Nantucket Harbor Estuarine System is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. The Nantucket Harbor System is presently supportive of infaunal habitat throughout its main basins, but is clearly impaired by nitrogen enrichment within the Head of the Harbor basin and in the eastern basin of Polpis Harbor, based upon eelgrass losses. Given the documented importance of eelgrass habitat to these basins and the demonstrable loss of eelgrass that were supported, eelgrass restoration in these basins was set as the primary nitrogen management goal for the overall System. Due to the semi-isolated nature of Polpis Harbor from Nantucket Harbor, it is necessary to establish 2 sentinel stations for eelgrass, one in the Head of the Harbor and one in the east basin of Polpis Harbor (e.g. where eelgrass had been observed in 1951-1989).
- It is important to note that the nitrogen levels throughout the Nantucket Harbor System remain relatively low, consistent with the oxygen conditions, lack of macroalgae and chlorophyll *a* levels. However, the water depth of the Harbor and possibly vertical and horizontal mixing rates appear to have resulted in a decline in eelgrass bed coverage from the deeper areas and more enclosed basin areas. While eelgrass was only recently lost from the east basin of Polpis Harbor, it is presently absent at a tidally average total nitrogen (TN) level of 0.361 mg N L⁻¹. Loss at this nitrogen level is consistent with observed losses in West Falmouth Harbor above 0.350 mg N L⁻¹, however, given the shallower depth of Polpis Harbor, it is likely that it is just slightly above its threshold level at present. Similarly, tidally averaged levels in the lower reach of Head of the Harbor (0.340-0.353) and mid and upper reach (0.390 mg N L⁻¹) also suggest that the recent bed losses are from a recent exceedance of the supportive nitrogen threshold. Given all of the factors discussed above and the similarity of Head of

the Harbor to conditions in West Falmouth and Phinneys Harbors and its present nitrogen levels, a nitrogen threshold of 0.350 mg N L⁻¹ was determined to be supportive of eelgrass habitat in this system. This threshold should also support eelgrass in the shallower regions as well. As the east basin of Polpis Harbor has only recently lost its eelgrass and is presently 0.361 mg N L⁻¹, but has shallower waters than Head of the Harbor, only a slight reduction over present levels appears to be needed to support eelgrass habitat. Clearly the threshold must be lower than the present 0.361 mg N L⁻¹ and higher than that for Head of the Harbor (0.350 mg N L⁻¹). Therefore, a threshold of 0.355 mg N L⁻¹ was set for the sentinel station in Polpis Harbor. It should be noted that the Polpis Harbor threshold is well constrained by the available data, but is at the limits of the sensitivity of the MEP approach.

It is important to note that the analysis of future nitrogen loading to the Nantucket Harbor 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 Nantucket Harbor estuarine system is that protection/restoration will necessitate a reduction in the present (2003) 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 Nantucket Harbor system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Nantucket Harbor system include both upper watershed regions contributing to the major surface water inputs.

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. ⁸ (mg/L)
NANTUCKET HARBOR SYSTEM										
Head of the Harbor	0.526	1.152	0.705	0.000	1.858	22.239	-17.211	6.886	0.34-0.41	--
Polpis Harbor	1.836	3.094	0.435	0.000	3.529	2.190	27.441	33.160	0.36-0.39	--
Quaise Basin	0.896	1.731	0.392	0.000	2.123	20.126	43.896	66.145	0.34	--
Town Basin	1.321	10.708	5.194	0.000	15.901	13.888	-2.793	26.997	0.30-0.34	--
Nantucket Harbor System Total	4.578	16.685	6.726	0.000	23.411	58.443	51.333	133.187	0.30-0.41	0.355

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 unattenuated 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 data collected between 1988 and 2005, ranges show the upper to lower regions (highest-lowest) of a sub-embayment.

⁸ Eel grass threshold for sentinel site located at Polpis Harbor.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Nantucket Harbor system. Two threshold scenarios are presented for the Harbor: Scenario A (N1) with 100% removal of septic load from the Town watershed together with 80% removal of anthropogenic watershed loads (septic, fertilizer and non-pervious surfaces) from the remaining three Harbor watersheds; and Scenario B (N2) with the removal of 100% of septic loads from all four of the Harbor Watersheds.

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
NANTUCKET HARBOR SYSTEM						
Head of the Harbor	1.858	N1: 0.792 N2: 1.153	22.239	N1: -16.795 N2: -17.182	N1: 6.235 N2: 6.210	N1: -57.4% N2: -37.9%
Polpis Harbor	3.529	N1: 2.175 N2: 3.093	2.190	N1: 26.450 N2: 26.655	N1: 30.816 N2: 31.939	N1: -38.4% N2: -12.3%
Quaise Basin	2.123	N1: 1.140 N2: 1.732	20.126	N1: 43.010 N2: 42.885	N1: 64.276 N2: 64.743	N1: -46.3% N2: -18.5%
Town Basin	15.901	N1: 10.707 N2: 10.707	13.888	N1: -2.892 N2: -2.892	N1: 21.702 N2: 21.702	N1: -32.7% N2: -32.7%
Nantucket Harbor System Total	23.411	N1: 14.814 N2: 16.685	58.443	N1: 49.772 N2: 49.466	N1: 123.029 N2: 124.594	N1: -36.7% N2: -28.7%

(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.