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Massachusetts Department of Environmental Protection

Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Lewis Bay Embayment System, Barnstable, 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 Lewis Bay embayment system, a coastal embayment primarily within the Town of Barnstable, Massachusetts. Analyses of the Lewis Bay embayment system was performed to assist the Towns of Barnstable and Yarmouth with up-coming nitrogen management decisions associated with the current and future wastewater planning efforts of the Towns, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and 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 Towns of Barnstable and Yarmouth 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 Lewis Bay embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Towns) for the restoration of the Lewis Bay embayment system.

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

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

In particular, the Lewis Bay embayment system within the Towns of Barnstable and Yarmouth 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 Towns of Barnstable and Yarmouth have recognized the severity of the problem of eutrophication and the need for watershed nutrient management and are currently developing Comprehensive Wastewater Management Plans, which each Town plans to implement. The Town of Barnstable has also completed and implemented wastewater planning in other regions of the Town not associated with the Lewis Bay embayment system. The Town has nutrient management activities related to their tidal embayments, which have been associated with the MEP effort in the Three Bays and the Centerville River/Harbor embayment systems. The Town of Barnstable and Yarmouth with associated work groups have recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making and alternatives analysis. The completion of this multi-step process has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, which is a partnership effort between all MEP collaborators and the Towns. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns' nutrient management groups to predict the impacts on water quality from a variety of proposed management scenarios.

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

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

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

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

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

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

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

Application of MEP Approach: The Linked Model was applied to the Lewis Bay embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Town of Barnstable, with technical guidance from the Coastal Systems Program at SMAST (see Chapter II). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Barnstable and Yarmouth Planning Departments, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Lewis Bay embayment system and each of the systems sub-embayments as appropriate (current and build-out loads are summarized in Chapter 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 Lewis Bay embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Vineyard Sound source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Lewis Bay embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the 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 Lewis Bay embayment system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for the Lewis Bay system. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

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 Lewis Bay embayment system in the Town of Barnstable and Yarmouth. 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 each embayment system. The concept was that since nitrogen loads associated with wastewater generally represent 57% - 81% of the controllable watershed load to the Lewis Bay embayment system and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through this source is a good gauge of the feasibility for restoration of these systems.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Lewis Bay embayment system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure. At present, the Lewis Bay system is showing variations in nitrogen enrichment and habitat quality among its various component basins. In general the system is showing healthy to moderately impaired benthic habitat. However, the smaller tributary embayments and limited inner areas of Lewis Bay (e.g. Uncle Roberts Cove, Hyannis Inner Harbor) are presently moderately impaired based upon infaunal habitat criteria. However, the dominant habitat issue for this system is the significant impairment of the Lewis Bay basin and Uncle Roberts Cove, based on eelgrass criteria. Historical eelgrass beds have been lost in these areas and eelgrass is virtually non-existent within this system. These significantly impaired habitats comprise ca. 90% of the estuarine area of the Lewis Bay Embayment System.

Overall, the oxygen levels within the major sub-basins to the Lewis Bay Embayment System are indicative of relatively healthy or only moderately impaired conditions. This is based on the definition of the Hyannis Inner Harbor and Mill Pond basins as infaunal habitats (e.g. historically have not supported eelgrass) and consideration of each sub-basins physical structure and natural biogeochemical cycling. Similar to other embayments in southeastern Massachusetts, the inner basins evaluated in this assessment showed high frequency variation, apparently related to diurnal and 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.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate moderately nutrient enriched waters within each sub-embayment basin to Lewis Bay. 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 match the spatial pattern of total nitrogen concentrations in this system. The parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

At present, eelgrass exists only within a small portion at the tidal inlet of Lewis Bay. The absence of eelgrass throughout the Lewis Bay Embayment System is consistent with the observed moderate level of nutrient enrichment throughout each of the sub-embayments to this complex estuary. Total nitrogen levels (TN) within the lower basins that supported eelgrass in 1951 (Lewis Bay and Uncle Roberts Cove) have mean summertime levels of ~0.4 mg N L^{-1} compared to the levels at the outer beds in adjacent Hyannis Harbor of 0.30-0.35 mg N L^{-1} (monitoring data, Chapter VI). Other key water quality indicators, dissolved oxygen and chlorophyll a, show similar levels of moderate enrichment with periodic oxygen depletions below 5-4 mg/L and chlorophyll levels of 3-6 ug/l to 2-10 ug/l in the Lewis Bay basin and 5-15 ug/L in Uncle Roberts Cove. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, the loss of eelgrass in these basins is expected.

The infaunal study indicated an overall system supporting generally healthy to only moderately impaired infaunal habitat relative to the ecosystem types represented (i.e. embayment versus salt marsh creek/pond). The range of habitat quality within Lewis Bay, results from a gradient in nutrient related habitat degradation from the inland reaches to the high quality habitat near the tidal inlet. This gradient continues into Hyannis Harbor and Uncle Roberts Cove. While the basin of Mill Creek is naturally nutrient and organic matter enriched, the present conditions of macroalgae and high chlorophyll a levels suggest a moderate level of impairment for this system as well.

Overall, the infaunal habitat quality was consistent with the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to it being dominated by wetlands versus being more characteristic of a tidal embayment. Based upon the MEP analysis it is clear that the tributary sub-embayment basins are presently supporting moderately to significantly impaired benthic habitat, while the main basin of Lewis Bay is generally of high quality. The Mill Creek basin is supporting moderately impaired habitat for a salt marsh basin. Impairment in these basins is through nitrogen and organic matter enrichment. The results of the Infauna Survey indicate that nitrogen management in the Lewis Bay watershed needs to include a lowering of the level of nitrogen enrichment in Hyannis Inner Harbor and Uncle Roberts Cove and potentially in Mill Creek thereby leading to restoration of nitrogen impaired benthic habitats. However, it is important to note that in general the Lewis Bay Embayment System is supportive of high quality infauna habitat throughout much basin area.

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 possibly 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 Barnstable Lewis Bay embayment system was comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 57% - 81% of the controllable watershed nitrogen load to the embayment was from wastewater.

A major finding of the MEP clearly indicates that a single total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of the Great, Green and Bournes Pond Systems, Popponesset Bay System, 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, inclusive of Lewis Bay.

The threshold nitrogen levels for the Lewis Bay embayment system in Barnstable and Yarmouth were determined as follows:

Lewis Bay Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Lewis Bay system should reflect both recent pre-degradation habitat quality and be reasonably achievable. Based upon the assessment data (Chapter VII), the Lewis Bay system is presently supportive of habitat in varying states of impairment, depending on the component sub-basins of the overall system.

- The primary habitat issue within the Lewis Bay Embayment System relates to the loss of the extensive eelgrass beds from Lewis Bay and the shallow marginal beds from Uncle Roberts Cove. This loss of eelgrass classifies these areas as "significantly impaired", although Lewis Bay presently supports generally high quality infaunal communities. The impairments to both the infaunal habitat and the eelgrass habitat within the component basins of the Lewis Bay Embayment System are supported by the variety of other indicators, oxygen depletion, chlorophyll, and TN levels, which support the conclusion that these impairments are the result of nitrogen enrichment, primarily from watershed nitrogen loading.

- The results of the water quality and infaunal data, coupled with the temporal trends in eelgrass coverage, clearly support the need to lower nitrogen levels within Lewis Bay and Uncle Roberts Cove in order to restore eelgrass habitat. Lesser loading reductions would be necessary within Hyannis Inner Harbor and potentially in Mill Creek for restoration of nitrogen impaired benthic habitats. Restoration of the limited areas of moderately impaired and areas of significantly impaired infaunal habitats within Lewis Bay and Uncle Roberts Cove, respectively, will be achieved with the restoration of eelgrass habitat within these basins.

- The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location (BHY-3) within Lewis Bay was determined to be 0.38 mg TN L^{-1}. As there is not high quality eelgrass habitat within the Lewis Bay Embayment System, this threshold was based upon comparison to other local embayments of similar depths and structure under MEP analysis as well as conditions near the eelgrass areas adjacent the tidal inlet to Hyannis Harbor. A well studied eelgrass bed within the lower Oyster River (Chatham) has been stable at a tidally averaged watercolumn TN of 0.37 mg N L^{-1}, while eelgrass was lost within the Lower Centerville River at a tidally averaged TN of 0.395 mg N L^{-1}, and also within Waquoit Bay at 0.39 mg N L^{-1}.

- The selection of the TN level for the shallow marginal bed within Uncle Roberts Cove followed the process noted in Chapter VIII for the selection of a sentinel station. Since water depth is important in determining the criteria for eelgrass restoration, as the same phytoplankton concentration that results in shading of eelgrass in deep water will allow sufficient light to support eelgrass in shallow water, the shallower water at the upper basin site allows for a higher TN level compared to the sentinel station. Analysis of comparable beds within the Green Pond Estuary (Falmouth) recommends the secondary criteria for this site as 0.40 mg TN L^{-1} for stability. The target nitrogen concentration for restoration of eelgrass within the lower basin of Green Pond, was determined to be 0.40 mg TN L^{-1} based in part upon the findings that: (1) eelgrass beds have been lost in that basin at 0.41 mg TN L^{-1}, although sparse eelgrass were observed adjacent the inlet, (2) eelgrass beds in Bournes Pond in very shallow water persisted at 0.42 mg TN L^{-1}. It should be noted that 0.40 mg N L-1 within Uncle Roberts Cove is a secondary criteria to ensure restoration of eelgrass habitat within this sub-embayment and should be met when the threshold is met at the sentinel station in Lewis Bay.

- Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fisheries resources), benthic infaunal habitat quality must also be supported as a secondary condition. At present, the regions with moderately impaired infaunal habitat within the Hyannis Inner Harbor and the potentially impaired habitat within Mill Creek have total nitrogen (TN) levels in the range of 0.518 - 0.574 mg N L^{-1}. Based upon observations discussed in Chapter VIII, the MEP Technical Team concluded that an upper limit of 0.50 mg N L^{-1} tidally averaged TN would support healthy infaunal habitat in the Lewis Bay System, specifically areas with moderately impaired infaunal habitat.

- For restoration of the Lewis Bay Embayment System, both the primary nitrogen threshold at the sentinel station and the secondary criteria within the sub-embayments need to be achieved. However, the secondary criteria established by the MEP are to merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station. Three secondary criteria were established for the Lewis Bay Embayment System: (1) a TN level of 0.40 mg N L^{-1} was set to restore the shallow marginal eelgrass bed within Uncle Roberts Cove (tidal average at BHY-4), this will also ensure restoration of infaunal habitat throughout that basin; (2) a tidally averaged TN level of <0.5 mg N L^{-1} with the Hyannis Inner Harbor basin (average of BH-1 and BH-2) and (3) a tidally averaged TN level of <0.5 mg N L^{-1} within the salt marsh basin of Mill Creek to reduce the magnitude of the phytoplankton blooms and improve infaunal habitat in the lower basin.

- Based upon all lines of evidence it appears that the Halls Creek Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment. Putting all the MEP habitat assessment elements together, it appears that for Halls Creek, the critical values are a total nitrogen level of 2 mg N L^{-1} in the headwaters (Station BC-13) and a level of 1 mg N L^{-1} at the border of the upper and lower reach (Station BC-14). As this upper/lower boundary station is the uppermost long-term marine water quality sampling site and integrates all of the watershed and upper marsh nitrogen inputs and removals, it was selected as the sentinel station for this system (BC-14). The threshold (tidally averaged) total nitrogen level of 1 mg N L^{-1} was determined to be appropriate for the sentinel station (BC-14).

For restoration of the Lewis Bay Embayment System, both the primary nitrogen threshold at the sentinel station and the secondary criteria within the sub-embayments need to be achieved. However, the secondary criteria established by the MEP are to merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station. It should be emphasized that these secondary criteria values were not used for setting nitrogen thresholds in this embayment system. The results of the Linked Watershed-Embayment modeling are used to ascertain that when the nitrogen threshold is attained, TN levels in the regions associated with the secondary criteria are within the acceptable range. The goal is to achieve the nitrogen target at the sentinel location and restore eelgrass habitat throughout Lewis Bay and Uncle Roberts Cove as well as infaunal habitat throughout the System

It is important to note that the analysis of future nitrogen loading to the Lewis Bay estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that significant increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. Therefore, watershed-estuarine nitrogen management must include management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Lewis Bay estuarine system is that restoration will necessitate a reduction in the present (2004) 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 Lewis Bay system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Surface water loads to estuarine waters of the Lewis Bay system are presented separately from the loads of the sub-embayments to which they discharge.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
LEWIS BAY SYSTEM										
groundwater sources										
Lewis Bay	0.564	4.364	26.490	0.000	30.855	13.507	25.999	70.361	0.37-0.43	0.38
Uncle Roberts Cove	0.096	0.148	0.392	0.000	0.540	0.759	12.771	14.069	0.41	0.40
Mill Creek	0.405	1.748	13.570	0.647	15.964	0.627	-1.535	15.056	0.52-0.56	0.50
Hyannis Inner Harbor	0.485	3.597	6.838	1.718	12.153	0.633	18.660	31.445	0.43-0.60	0.50
Snows Creek	0.293	2.118	4.907	8.090	15.115	-	-4.533	10.582	1.57	--
Stewarts Creek	0.485	4.312	15.756	18.923	38.992	0.236	-9.750	29.478	1.25	--
surface water sources										
Chase Brook [a]	0.140	1.077	2.268	0.000	3.345	-	-	3.345	-	--
Mill Pond Creek [a]	1.033	4.225	10.389	0.425	15.038	-	-	15.038	-	--
Inner Harbor Creek [b]	0.060	0.326	1.581	0.000	1.907	-	-	1.907	-	--
Lewis Bay System Total	3.562	21.915	82.192	29.803	133.909	15.762	41.612	191.283	**0.37-1.57**	**0.38**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing attenuated wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings (the sum of land use, septic, and WWTF loading)
[5] atmospheric deposition to embayment surface only. Atmospheric loads to surface water inputs are included with their respective watershed load.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 2001 – 2006 data, ranges show the upper to lower regions (highest-lowest) of a sub-embayment.
[8] Eel grass threshold for sentinel site located in Lewis Bay (0.38 mg/L), and infaunal targets at remaining stations.
[a] Surface water discharge to Mill Creek
[b] Surface water discharge to Hyannis Inner Harbor

Table ES-2. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Halls Creek system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Halls Creek 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)
HALLS CREEK SYSTEM										
Halls Creek	0.844	6.266	15.268	0.000	21.534	0.630	5.252	27.416	0.43-0.45	1.00
Halls Creek (freshwater)	0.060	0.110	0.351	1.137	1.597	-	-	1.597	1.21	
Halls Creek System Total	0.904	6.375	15.619	1.137	23.131	0.630	5.252	29.013	**0.43-1.21**	**1.00**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing attenuated wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings (the sum of land use, septic, and WWTF loading)
[5] atmospheric deposition to embayment surface only.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of data collected between 2001 and 2006, ranges show the upper to lower regions (highest-lowest) of the indicated sub-embayment.
[8] threshold for sentinel site located at mid-point WQ monitoring station of the system.

Table ES-3. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Lewis Bay system.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
LEWIS BAY SYSTEM						
groundwater sources						
Lewis Bay	30.855	9.663	13.507	23.916	47.086	-68.7%
Uncle Roberts Cove	0.540	0.54	0.759	10.991	12.290	0.0%
Mill Creek	15.964	4.321	0.627	-1.208	3.740	-72.9%
Hyannis Inner Harbor	12.153	7.115	0.633	9.780	17.528	-41.5%
Snows Creek	15.115	16.233	-	-4.533	11.700	+7.4%
Stewarts Creek	38.992	41.605	0.236	-10.402	31.439	+6.7%
surface water sources						
Chase Brook	3.345	3.337	-	-	3.337	-0.2%
Mill Pond Creek	15.038	14.682	-	-	14.682	-2.4%
Inner Harbor Creek	1.907	0.326	-	-	0.326	-82.9%
Lewis Bay System Total	133.909	97.822	15.762	23.916	137.500	-26.9%

(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.

Table ES-4. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Halls Creek system.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent change in watershed load to achieve allowed threshold load levels
HALLS CREEK SYSTEM						
Halls Creek	21.534	32.918	0.630	6.649	40.197	+52.9%
Halls Creek (freshwater)	1.597	3.345	-	-	3.345	+109.4%
Halls Creek System Total	23.131	36.263	0.630	6.649	43.542	+56.8%

(1) Composed of combined natural background, fertilizer, runoff, and septic system loadings.
(2) Target threshold watershed load is the load from the watershed that meets 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.