SMAST University of Massachusetts Dartmouth
The School for Marine Science and Technology

Massachusetts Department of Environmental Protection

Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Rock Harbor Embayment System, Town of Orleans, 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 Rock Harbor embayment system, a coastal embayment situated within the Town of Orleans, Massachusetts. Analyses of the Rock Harbor embayment system was performed to assist the Town with up-coming nitrogen management decisions associated with 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 Orleans 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 Rock 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 / protection of the Rock 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 Rock Harbor embayment system within the Town of Orleans is at risk of eutrophication (over enrichment) in its lower reaches due to enhanced nitrogen loads entering through groundwater and surface water from the increasingly developed watersheds to this complicated estuarine system that includes significant areas of salt marsh. 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 that exist in the Rock Harbor watershed (including the Town of Eastham) have recognized the severity of the problem of eutrophication and the need for watershed nutrient management. Concern over declining resource quality of the estuarine systems of Orleans (inclusive of Rock Harbor) prompted the Town of Orleans to initiate the town-wide Orleans Water Quality Monitoring Program in 2001, which continues in a reduced form through present (2008). The 2001 Program was an expansion of a previous effort targeting Pleasant Bay, begun in 1997 by the Orleans Water Quality Task Force. The town-wide monitoring program is focused on restoring and protecting the estuarine habitats associated with the Town of Orleans and is being undertaken in concert with the DEP/SMAST Massachusetts Estuaries Project. This is a collaborative effort whereby the Town of Orleans provides the support, coordination and oversight of the program through its Planning Office and through its Wastewater Management Steering Committee and SMAST provides the technical and analytical aspects needed for the project through the MEP Technical Team.

The investigations undertaken prior to the Massachusetts Estuaries Project analysis summarized in this report provided significant information related directly to the implementation of the MEP Linked Management Modeling Approach and helped yield insight into the interpretation of the results. In addition, the Town of Orleans' comprehensive Water Quality Monitoring Program was of sufficient rigor to be used as the water quality baseline required for the MEP threshold analysis presented in this MEP Technical Report.

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 Rock Harbor embayment system by using site-specific data collected by the MEP and water quality data from the Orleans Water Quality Task Force Water Quality Monitoring Programs (see Chapter 2). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Planning Departments in each of the Towns represented in the Rock Harbor watershed, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Rock Harbor embayment system and associated sub-embayments (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 Rock Harbor embayment system. Once the hydrodynamic properties of the estuarine system was 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 bio-available and total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis while nitrogen entering the coastal embayment was quantified by direct measurement of stream nutrient concentrations and freshwater flow, predominantly groundwater, in streams discharging directly to the embayment. Boundary nutrient concentrations in the Cape Cod Bay source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Rock 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 approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout and embayment system, is to first identify a sentinel location within the embayment and second to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality (threshold nitrogen level). The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined, the Linked Watershed-Embayment Model is used to adjust nitrogen loads sequentially until the targeted nitrogen concentration is achieved. For the Rock Harbor System, the restoration target should reflect both recent pre-degradation habitat quality and be reasonably achievable. The load reductions presented in the report represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation in this report of load reductions aims 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 Rock Harbor embayment system (a unique combination of salt marsh and open water in the form of an artificially created open water basin). Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. These scenarios should be developed in coordination with both the Towns in the Rock Harbor watershed in order to effectively examine the effect of load reductions on water column nutrient concentrations. 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 septic system nitrogen loads generally represent 88%-92% of the controllable watershed load to the Rock 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 restoration of these systems.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout Rock Harbor system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. The Rock Harbor system is showing high habitat quality throughout its upper salt marsh reach (above WMO-17) and significant habitat impairment in its lower "embayment" reach (e.g. harbor portion, WMO-17 to inlet). The upper reach appears to be a fully functional tidal salt marsh with deeply incised narrow creeks surrounded by significant areas of emergent marsh. This reach is typical of New England "pocket" marshes, with smaller tidal creeks and a marsh plain dominated by low marsh and high marsh plant communities, along with patches of fringing brackish marsh vegetation.

In Contrast, the lower "embayment reach, comprised primarily of the harbor basin, functions as a small open water cove or harbor. This basin is depositional by structure, collecting both algal and salt marsh organic matter with accumulation of anoxic organic-rich fine sediments (sulfidic); it is highly tidal, with sufficient light penetration to allow periodic development of benthic algal mats; and its tidal inlet is influenced by sand transport via nearshore coastal processes associated with adjacent Cape Cod Bay. These features in combination with the observed levels of summer oxygen depletion (to 2 mg L^{-1}), indicate a significantly impaired habitat. This assessment is supported by the impoverished infaunal animal community which is dominated by small opportunistic stress indicator species common to disturbed or organic matter enriched basins.

Based upon all available information the present lack of eelgrass throughout the Rock Harbor System does not appear to be a response to watershed sourced nitrogen loading (e.g. changing watershed land-use). Instead, the absence of eelgrass habitat appears to result from the structure of the upper reach supportive of salt marsh and the lower reach being a maintained depositional basin. The absence of eelgrass within the harbor basin is likely the result of its configuration, in that it is a "relatively deep" depositional basin. In addition, in the lower reach, harbor activities also likely have limited the potential for colonization of this system. Most important relative to MEP nitrogen thresholds analysis, it does not appear that eelgrass beds have been present within the Rock Harbor System at any time over the past century, as indicated by MassDEP Eelgrass Mapping Program analysis and MEP Technical Team historical analysis. Therefore, nitrogen threshold development for protection/restoration of this estuarine system will necessarily focus on restoration of the impaired infaunal habitat within the harbor (embayment reach) and protection of the high quality infaunal habitat within the upper salt marsh reach

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 each of the sub-embayment systems in this study were developed to restore or maintain SA waters or high habitat quality. In these systems, high habitat quality was defined as supportive of diverse benthic benthos animal communities. Dissolved oxygen and chlorophyll *a* were also considered in the assessment.

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Rock Harbor embayment system was comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 88%-92% of the controllable watershed nitrogen load to the embayment was from wastewater.

The Rock Harbor estuary is a composite of 2 different estuarine systems; an upper salt marsh reach and a lower embayment reach (the harbor). These systems have very different tolerances to nitrogen enrichment and are presently supporting habitats of very different quality, with high quality habitat in the salt marsh and significantly impaired habitat quality within the embayment (Table VIII-1). Since the embayment reach is clearly over its ability to assimilate its

present nitrogen load without impairment, restoration will require nitrogen management. A correlative effect of nitrogen management will be that nitrogen loading to the upper salt marsh will also be reduced, although the upper salt marsh is well below its likely nitrogen loading threshold level to maintain its high quality habitats. Therefore the nitrogen threshold for the Rock Harbor System focusing on the habitat quality of the embayment reach will necessarily be protective of the upper salt marsh reach.

The threshold nitrogen levels for the Rock Harbor embayment system in the Towns of Orleans and Eastham were determined as follows:

Rock Harbor Threshold Nitrogen Concentrations

- As a result of the present significant impairment of the infaunal habitat within the embayment reach of the Rock Harbor Estuary and given that there is no evidence that this system has supported eelgrass over the past century, the threshold development necessarily focuses on the embayment reach. The threshold for restoring and maintaining high quality infaunal habitat within the embayment reach of Rock Harbor is 0.500 mg TN L^{-1} (tidally averaged) at the sentinel station located at the head of the harbor (upper region of harbor basin, Town of Orleans Water Quality Monitoring Program station WMO-17). .

- At present, the embayment reach of the Rock Harbor System has elevated total nitrogen levels (0.686 mg N L^{-1}, tidally averaged), with stressful levels of summer oxygen depletion (to 2 mg L^{-1}), sulfidic sediments and depleted infaunal communities dominated by stress indicator species. These observations strongly support the contention that this basin is significantly impaired through nitrogen enrichment. As this basin does not presently support high quality infaunal habitat, the nitrogen threshold analysis was based upon comparisons to a number of small embayments on Cape Cod.

- Based upon these observations, 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 lower embayment reach of the Rock Harbor System. Equally important, lowering nitrogen levels from the present 0.686 mg N L^{-1} to the threshold 0.500 mg N L^{-1} will lower nitrogen levels within the upper salt marsh (e.g. WMO-18, from 0.829 to 0.615 mg N L^{-1}), protective of those habitats. Therefore, it appears that achieving the nitrogen target at the sentinel location is restorative of infaunal habitat throughout the lower basin and protective of habitats within the upper salt marsh reach.

- The nitrogen concentration thresholds developed through the MEP analysis were used to determine the amount of total nitrogen mass loading reduction required for restoration of infaunal habitats in the Rock Harbor system. 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 Rock Harbor. 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 in the report represent only one of a suite of potential reduction approaches that need to be evaluated by the community. As discussed in Chapter 8, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required nearly 70% removal

of septic load (associated with direct groundwater discharge to the embayment) for the entire system. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1

It is important to note that the analysis of future nitrogen loading to the Rock Harbor 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 (presently less than half of the parcels use lawn 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 Rock Harbor estuarine system is that restoration will necessitate a reduction in the present 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 Rock Harbor system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Rock 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)
ROCK HARBOR SYSTEM										
Rock Harbor	0.822	1.126	6.787	0.065	7.978	0.079	1.382	9.4393	0.66-1.10	--
Rock Harbor Creek	0.107	0.177	0.910	-	1.088	0.000	0.000	1.088	1.14	--
Rock Harbor System Total	0.929	1.303	7.698	0.065	9.066	0.079	1.382	10.527	**0.66-1.14**	**0.500**

[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 2001 and 2006, ranges show the upper to lower regions (highest-lowest) of the indicated sub-embayment.
[8] benthic infauna threshold for sentinel site located at the head of the lower basin of the Harbor system.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Acushnet River 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
ROCK HARBOR SYSTEM						
Upper Basin	7.978	2.633	0.079	1.207	3.919	-67.0%
Acushnet River (fresh water)	1.088	1.088	0.000	0.000	1.088	0.0%
Rock Harbor System Total	9.066	3.720	0.079	1.207	5.006	-59.0%

(1) Composed of combined natural background, fertilizer, runoff, WWTF, 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.