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Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Sesachacha Pond, Nantucket, Massachusetts

Executive Summary

1. Background

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Sesachacha Pond embayment system, a coastal embayment of the Island of Nantucket within the Town of Nantucket, Massachusetts. Analyses of the Sesachacha Pond embayment system was performed to assist the Town with up-coming nitrogen management decisions associated with the Towns' current and future wastewater planning efforts, as well as wetland restoration, anadromous fish runs, shell fishery, and open-space 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/macroalgal 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 Sesachacha Pond embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Town) for the restoration of the Sesachacha Pond 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 Sesachacha Pond embayment system within the Town of Nantucket is showing signs of eutrophication (over enrichment) from extremely limited tidal exchange with clean Atlantic Ocean water, atmospheric deposition, flux of nutrients from bottom sediments, as well as and to a lesser extent, 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, Harbor and pond waters has historically been a valuable asset to the island. However, concern over the potential degradation of pond and Harbor water quality began to arise, which resulted in monitoring, scientific investigations and management planning which continues to this day. While Sesachacha Pond presently has a relatively low nitrogen load from its watershed, due to its small watershed and proportionally large undeveloped areas, it is still significantly impaired by nitrogen enrichment and is clearly eutrophic. This apparent paradox results from its very low tidal exchange rate, resulting from barrier beach processes closing the inlet to the Atlantic Ocean on an annual basis. The highly restricted "flushing" of pond waters per annum serves to greatly increase the nitrogen sensitivity of this system, such that even low rates of nitrogen loading cause eutrophic conditions. The difficulty in achieving adequate tidal exchange during any given opening attempt has resulted in the present ecological impairment of the Sesachacha Pond System. The low rate of nitrogen removal through tidal flushing results in high nitrogen levels, large phytoplankton blooms and periodic anoxia of bottom waters. As such, 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 restoration. 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 and the Islands (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 Sesachacha Pond embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Nantucket Marine Department, with technical guidance from the Coastal Systems Program at SMAST (see Section II). Evaluation of upland nitrogen loading was conducted by the MEP. Estuaries Project staff obtained digital parcel and tax assessors data from the Town of Nantucket Geographic Information Systems Department, watershed specific water use data from the Wannacomet Water Company (WWC) and watershed boundaries adopted by the town as the Harbor Watershed Protection District (<http://www.nantucket-ma.gov>). During the development of the Nantucket Water Resources Management Plan, an island-wide groundwater mapping project, using many of the USGS wells on the Island, was completed to characterize the water table configuration of Nantucket (Horsley, Witten, 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, Witten and Hegeman, Inc. (HWH) to complete the watershed delineations for Nantucket including Sesachacha Pond (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 Sesachacha Pond embayment system (current and build-out loads are summarized in Section IV). Water quality within an embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this estuarine system, which is periodically open to tidal forcing, 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 (during breach events) developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents during breach events and water elevations was employed for the Sesachacha Pond embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Atlantic Ocean source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Sesachacha Pond embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the embayments.

MEP Nitrogen Thresholds Analysis: The threshold nitrogen level for an embayment represents the average water column concentration of nitrogen that will support the habitat quality being sought. The water column nitrogen level is ultimately controlled by the watershed nitrogen load and the nitrogen concentration in the inflowing tidal waters during breach events (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 infaunal communities. Dissolved oxygen and chlorophyll a were also considered in the assessment.

After developing the dispersion-mass balance model of Sesachacha Pond to simulate conditions that exist as a result of present management practices, the model was used to simulate a modified management approach that could be followed to improve water quality conditions in the pond year-round. The habitat quality in Sesachacha Pond has been historically moderate to poor, depending on the intensity of management, specifically the frequency and duration of openings to the ocean. To that effect, with a goal of seeking further improvements in water quality conditions in the Pond, an alternate management scheme was modeled using the dispersion-mass balance model developed for Sesachacha Pond. One goal of this proposed management scenario is to prevent salinity in the pond from dropping below 22 ppt at any point of the year. Another goal is to reduce TN concentrations in the pond during the summer months, when benthic regeneration and algae production is greatest. A simple way to achieve these goals is to add an additional mid-summer breach event each year.

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 Sesachacha Pond embayment system in the Town of Nantucket. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. Since Sesachacha Pond currently has a low watershed nitrogen load, with external loading dominated by direct atmospheric input, and moderate summer input from its sediments and only periodic tidal exchange, the MEP analysis has initially

focused upon modifying the breaching schedule for the Pond as a means of reaching a threshold water column nitrogen concentration supportive of infauna.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Sesachacha Pond system based upon available water quality monitoring data, distribution of macroalgae, time-series water column oxygen measurements, and benthic community structure. At present, eelgrass is not found within Sesachacha Pond. The current lack of eelgrass beds is expected given the high chlorophyll a and low dissolved oxygen levels as well as water column nitrogen concentrations within this system. In addition, it does not appear that eelgrass beds have been present in this system at any time over the past century, due to the systems only periodic tidal exchange and "naturally" nitrogen enriched condition. Therefore, habitat restoration in this eutrophic system should focus on infaunal habitat quality.

The effect of nitrogen enrichment and extremely limited tidal flushing as is the case in Sesachacha Pond 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 ~7-8 mg L⁻¹ at the mooring sites). The dissolved oxygen records indicate that the Sesachacha Pond system is currently under seasonal oxygen stress, consistent with its significant nitrogen enrichment. Nitrogen levels are frequently in the range of 1.0 -1.5 mg TN L⁻¹ between pond openings (Chapter VI). That the cause of habitat impairment in this system is eutrophication is supported by the high levels of chlorophyll a, >25 µg/L 55% of the time (Table VII-2). Oxygen conditions and chlorophyll a levels improve in the fall and winter, although the system showed oxygen depletions in late summer below 5 mg L⁻¹ (21% of the deployment record) and <3 mg L⁻¹ (5% of the deployment record of 67 days). The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate highly nutrient enriched waters and significantly impaired habitat quality within this salt pond

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Sesachacha Pond is presently supporting significantly to severely degraded benthic infauna habitat quality. In virtually all samples a single species indicative of organic matter enriched conditions, *Streblospio benedicti*, was dominant, typically accounting for more than two thirds of the individuals present. While most stations along the eastern (A) and western (C) transects had moderate numbers of individuals, the number of species was low (≤ 6), in 90% of the samples and species diversity (0.05-1.82) indicative of poor habitat quality. The middle transect (B) showed an impoverished community with total individuals at the 5 sites being only 16-72 per sample. The MEP infauna survey results clearly indicate that Sesachacha Pond is presently supporting significantly impaired to severely degraded benthic infaunal habitat and the communities present are consistent with organic matter enrichment associated with nitrogen enrichment of pond waters. However, it appears that the system should be capable of supporting healthy infaunal communities should the organic matter loadings be reduced.

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 during breach events. 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 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, Sesachacha Pond embayment system was comprised primarily of runoff from impervious surfaces, fertilizers and wastewater nitrogen. Land-use and wastewater analysis found that generally about 25% of the controllable watershed nitrogen load to the embayment was from wastewater and 10 percent was from fertilizers.

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 level for the Sesachacha Pond embayment system in Nantucket was determined as follows:

Sesachacha Pond Threshold Nitrogen Concentrations

- With a goal of seeking further improvements in water quality conditions in the Pond, an alternate management scheme was modeled using the dispersion-mass balance model developed for Sesachacha Pond. One goal of this proposed management scenario is to prevent salinity in the pond from dropping below 22 ppt at any point of the year. Another goal is to reduce TN concentrations in the pond during the summer months, when benthic regeneration and algae production is greatest. Both of these goals are related, as better flushing management results in both higher salinities and lower nitrogen levels in pond waters. A simple way to achieve these goals is to add an additional mid-summer breach event each year.
- Model results indicate that water quality improvements that may provide more stable environment for flora and fauna is possible with the addition of a successful mid-summer breach. Data indicate that openings as short as six days are sufficient to provide sufficient tidal flushing and raise salinity levels near 30 ppt. Pond salinity is a useful indicator of breach success, as opposed to the duration of the opening. With the mid-summer breach, it should be possible to maintain salinities above 25 ppt and TN concentrations below 1.00 mg/L.

- A significant improvement in the nitrogen related health of Sesachacha Pond infaunal animal habitat would result from the modeled addition of a mid summer opening. It would be possible to use the monthly monitoring data to indicate when the mid-summer breach should occur. The primary indicator would be when the pond salinity drops below 25 ppt. The secondary indicator would be when the pond TN concentration rises above 0.95 mg/L. If this strategy is followed in the future, the result would be year-round salinities above 22 ppt and TN concentrations below 1.00 mg/L. It is important to note that the modeled maximum and average TN levels are likely conservative estimates as they do not include potential reductions in the rate of sediment nitrogen regeneration often associated with the lowering of nitrogen enrichment of embayment waters.
- It should be noted that the above mentioned management scenarios oriented around altering the timing of breaches of the barrier beach, effective as these may be, are contingent on the ability of the Town of Nantucket to obtain necessary permitting of such actions. Breaching of the barrier beach is necessarily subject to compliance with applicable federal, state and local statutes and regulations.

It is important to note that the analysis of future nitrogen loading to the Sesachacha Pond estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. In the case of the Sesachacha Pond watershed, these potential increases are likely to be slight. Nevertheless, given the highly over-loaded state of the system, watershed-estuarine nitrogen management should consider 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 Sesachacha Pond estuarine system is that restoration will necessitate a modified breaching schedule for the pond in order to enhance flushing with low nutrient, clean Atlantic Ocean waters. Reduction in the present (2003) nitrogen inputs and management options to negate additional future nitrogen inputs should also be considered in the context of additional breaching.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Sesachacha Pond system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Sesachacha Pond 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)
Sesachacha Pond System Total	0.575	0.871	0.101	0.000	0.973	3.115	20.376	24.464	1.20	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 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 1992 – 2005 data.
- ⁸ maximum annual TN concentration

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Sesachacha Pond 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
Sesachacha Pond System Total	0.973	0.973	3.115	20.376	24.464	0.0%

- (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.