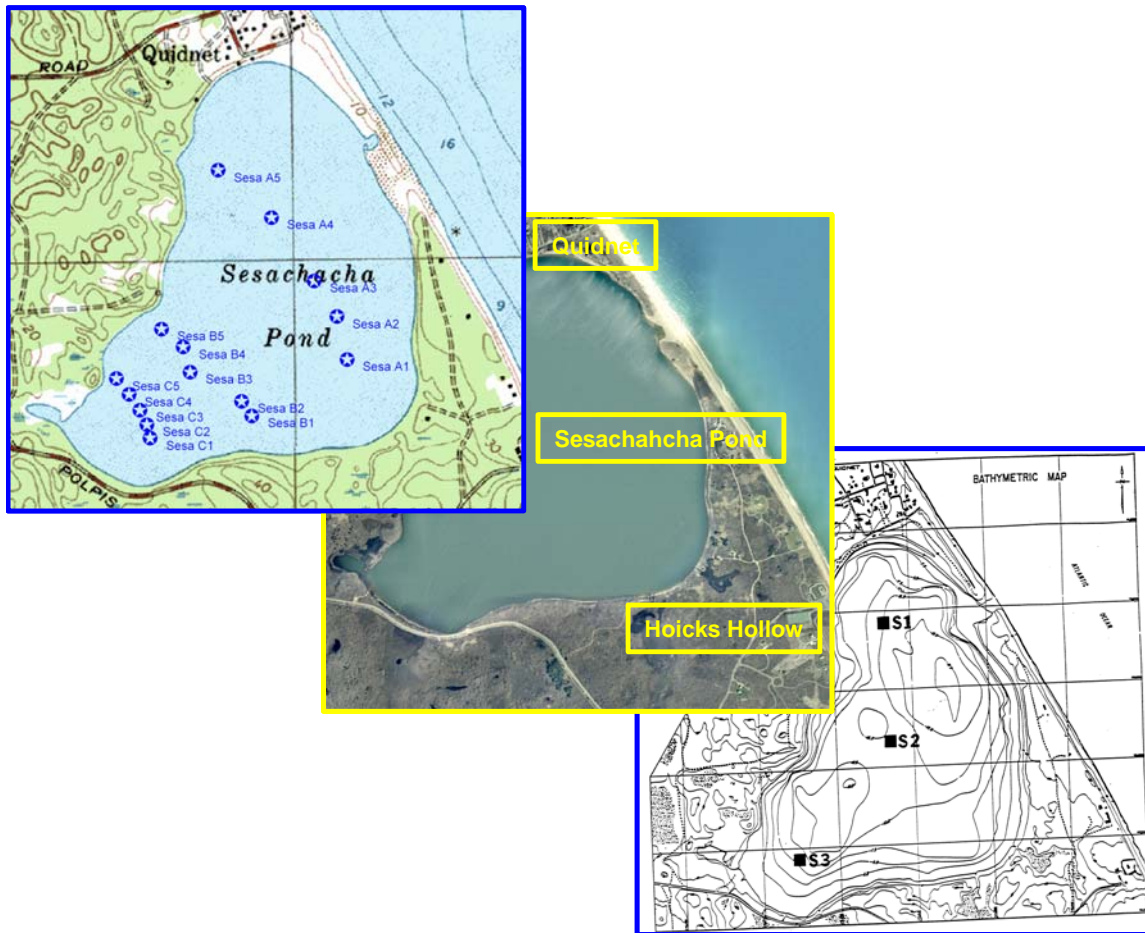# Massachusetts Estuaries Project

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

University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

FINAL REPORT – NOVEMBER 2006

Massachusetts Estuaries Project

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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

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.

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 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.

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.

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I. INTRODUCTION

The Sesachacha Pond Embayment is a simple estuary located within the Town of Nantucket on the Island of Nantucket, Massachusetts. Sesachacha Pond is stabilized as an estuarine system by periodic management breaching of the barrier beach which separates the salt pond from the marine waters of the Atlantic Ocean (Figure I-1 and I-2). The Pond is breached 2-3 times per year to lower its nitrogen levels and raise its salinity through the exchange of brackish pond waters with the high quality offshore waters. Pond openings are also to allow the entry of marine larvae and potentially herring. Studies of Sesachacha Pond in the late 1980's indicated that periodic tidal exchange was required to help stabilize the ecology. Data indicated that not breaching the Pond regularly for management would result in long term cycling of pond waters between saline and near freshwater (~1 ppt), due to the freshening by groundwater inflow and periodic storm inflows of salt water (Howes and Goehringer 1989). This salinity cycling would result in highly unstable conditions and impairment of habitat quality. The natural breaching of the barrier beach was subsequently observed during Hurricane Bob in 1991. Sesachacha Pond has been breached for management purposes for more than a century, with greater and lesser success. However, it is clear that the health of this estuary's habitats are dependent on the amount and timing of periodic tidal exchanges. One of the goals of the MEP analysis was to determine the best protocol for pond openings aimed at producing the highest quality habitat within this embayment.

Figure I-1.   Location of the Sesachacha Pond system, Island of Nantucket, Town of Nantucket, Massachusetts. Sesachacha Pond is a great salt pond, historically maintained by periodic breaching of the barrier beach to allow exchange with Atlantic Ocean waters.

Figure I-2.   Study region for the Massachusetts Estuaries Project analysis of the Sesachacha Pond System. Tidal waters enter the Pond from the Atlantic Ocean during periodic openings of the barrier beach. Freshwaters enter from the watershed primarily through direct groundwater discharge and direct precipitation.

Sesachacha Pond is approximately 6.0 miles northeast of the Nantucket town center and its watershed abuts the watershed to Nantucket Harbor. Sesachacha Pond is situated on the eastern coast of Nantucket Island between Squam Head and Sankaty Head. The watershed to Sesachacha Pond is fully within the Town of Nantucket, making Nantucket the sole municipal steward of this small estuary. Virtually all watershed freshwater and nutrients enter Sesachacha Pond via groundwater seepage, as there are no significant surface inflows to this system. As a result, there is little opportunity for nitrogen removal during transport from watershed source to estuarine waters.

Sesachacha Pond is comprised of a single basin and a narrow barrier beach which is periodically breached to the Atlantic Ocean for pond management. The open water area of 255-267 acres makes Sesachacha Pond a great salt pond. Sesachacha Pond was formed by the flooding of a kettle pond as a result of rising sea level following the last glaciation approximately 18,000 years BP. Sesachacha Pond consists of two deep "holes", reaching a maximum depth of 6.6 meters, and 3 functional sub-basin areas. The pond is approximately 1,320 meters long and is oriented north-northeast paralleling the shore of the Atlantic Ocean. The maximum width of the pond is 1,200 meters with an irregular shore that makes for an average width of approximately 850 meters. The pond possesses approximately 5.5 kilometers of shoreline, 870 meters of which is on the inland shore of the barrier beach separating the Pond from the Atlantic Ocean. The Pond is non-tidal and the salinity is maintained by periodic breaching of the barrier beach by the Town. Water levels vary from a low immediately after a breaching event and a high after an extended period of closure, which allows groundwater inflow to raise pond levels and dilute the salinity of pond waters.

Sesachacha Pond is predominantly groundwater fed with no significant surface inflows of freshwater. The Town openings of the channel from the Pond to the Atlantic Ocean is to enhance flushing of the Pond, maintain "acceptable" levels of salinity and nitrogen within the Pond waters and to allow for entry of marine organisms (e.g. fish and larvae). Generally, Sesachacha Pond is a brackish waterbody with salinities ranging between 10 – 25 ppt with salinities increasing to approximately 32 ppt during times when the Pond is opened to the Atlantic Ocean. Analysis of the long term record of the surface water salinity of the Pond indicates that with proper management salinities can be maintained at levels $\geq$20 ppt (Chapter VI).

Recent Management History:

Historically, Sesachacha Pond has been opened to tidal exchange each spring and fall to maintain salinity, manage nutrients and to allow passage of marine larvae and herring. The pond was not opened from 1981-1991, resulting in a freshening of Pond waters and a loss of all marine species (Howes and Goehringer 1989). After a decision to again manage the Pond as a "marine" resource area, the pond has been opened to Atlantic Ocean waters each spring and fall over the past decade, with openings persisting for 3.5 to 25 days per year (Curley 2004). During closed periods, groundwater inflow dilutes pond salinities periodically to ~10 ppt and raises pond levels by several feet. Water quality within this system is primarily controlled by the frequency and duration of openings to tidal exchange. There is very little nitrogen loading from development within the relatively small watershed to this great salt pond system and atmospheric deposition of nitrogen is the major source of external nitrogen to pond waters (Chapter IV). The embayment has traditionally been managed as a source of seed shellfish, although there are anecdotal reports of significant shellfish harvest from this system.

Based on the soundings, the depth of Sesachacha Pond averages approximately 5.5 meters. There are two deep basins (basin 1 and basin 2) 6.6 meters and 6.1 meters respectively, with a third less distinct basin being shallower, 4.3 m (Figure I-3). Basin 1 is the deepest of the three basins making up Sesachacha Pond and is situated in the northeastern quadrant of the pond closest to the location of historical and future breaches of the barrier beach. Moreover, this deepest of the three basins is closest to the area of the pond that supports the greatest extent of residential development.

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 due to barrier beach processes closing the inlet to the Atlantic Ocean on an annual basis. As presented in a Sesachacha Pond 1989 Draft Environmental Impact Report (EIR), the barrier beach separating Sesachacha Pond from the Atlantic Ocean was dredged out once and sometimes twice per year as far back as the 1930's. This cycle of periodic openings continued generally uninterrupted up until 1981. The man-made breach to the pond was developed using the hydraulic gradient between the pond and the ocean to create a rapid outflow of pondwater to scour a channel in the barrier beach to a depth low enough to allow tidal exchange to occur for as long as possible (1-14 days). Infrequently the opening was reported to have stayed open for longer than two weeks. These periodic openings were undertaken as a means of controlling salinity in the pond in order to safeguard shellfish resources as well as allow for the passage of finfish into the pond, lower pond levels as a flood control measure, and allow nutrient rich waters to flush out of the pond as a water quality control measure.

Figure I-3. Sesachacha Pond bathymetry depicting major basins, Town of Nantucket, Massachusetts (EIR 1989).

In the early 1980's ownership of the land that constitutes the barrier beach resided with a Mrs. Evans who reportedly initiated a study of the impact of periodic breaching on the pond. A hydrogeologic investigation of Sesachacha Pond was completed in 1985 (Perkins Jordan 1985), with the goal of understanding the interaction of the pond with surrounding groundwater and evaluate the long term changes in the quality of the pond water due to opening the pond to the ocean. It was reported in the 1989 Draft EIR of Sesachacha Pond that based on the findings of the hydrogeologic study, annual dredging of the pond was suspended for a period of time. In 1987, the barrier beach property changed ownership (Greenhill) at which point outstanding questions related to the value of pond openings on maintaining the ecological function of the system resurfaced. To address the pond opening issue, a scientific study to determine the likely impacts of various pond management alternatives on Sesachacha Pond and surrounding wetlands was initiated by the Greenhills and the Massachusetts Audubon Society. Based upon the data generated by this effort showing that the Pond habitats are best managed as estuarine

4

resources and that periodic opening are required to achieve the needed conditions. The 1989 EIR was developed and the Pond once again was breached for management.

As presented in various Sesachacha Pond Annual Reports (as far back as 1992) developed by the Town of Nantucket Shellfish and Marine Department, the Pond again opened in 1991 and periodically opened in each subsequent year to allow exchange with Atlantic Ocean water. However, 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. It is clear that restoration of Sesachacha Pond will require evaluating the timing and duration of the periodic openings that would achieve the highest habitat quality within this system, relative to the logistical realities involved.

Although the nitrogen load to Sesachacha Pond is relatively low and dominated by atmospheric inputs, nitrogen management still needs to be evaluated in the development of the restoration and management plan. The Town of Nantucket has been among the steadily growing towns in the Commonwealth over the past two decades and does have a centralized wastewater treatment system that services the town center. However, the Sesachacha Pond watershed, being situated in a relatively remote and undeveloped area of the Island is not connected to any municipal sewerage system, but relies on privately maintained septic systems for treatment and disposal of wastewater. As existing and probable increasing levels of nutrients impact Nantucket's coastal embayments, water quality degradation will accelerate, with further harm to invaluable environmental resources.

As the stakeholder to the Sesachacha Pond System, the Town of Nantucket and its citizens have been active in promoting restoration of the coastal embayment systems of the Island. This local concern also led to the conduct of several studies (Section Chapter II) to support monitoring and restoration and the Town is presently willing to implement an appropriate plan for estuarine restoration. To this end, the Town of Nantucket Water Quality Monitoring Program was provided technical assistance by the Coastal Systems Program at SMAST-UMD and over the past several years has been able to develop a significant baseline of water quality in the embayments of the Island inclusive of Sesechacha Pond. This effort provides the quantitative water column nitrogen data (1988-89; 2000-2005) required for the implementation of the MEP's Linked Watershed-Embayment Approach used in the present study.

The common focus of the Nantucket water quality monitoring effort has been to gather site-specific data on the current nitrogen related water quality throughout the Sesachacha Pond System and determine its relationship to tidal flushing when the pond is opened to the ocean. This multi-year effort has provided the baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. The MEP effort builds upon the Water Quality Monitoring Program, previous hydrodynamic studies and water quality analyses and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for each major sub-embayment. These critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to develop and implement management alternatives needed by the Town of Nantucket for estuarine restoration/protection. While the completion of this complex multi-step process of rigorous scientific investigation to support watershed and tidal flushing

based nitrogen management plans has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff and citizens over many years, most notably within the Shellfish and Marine Department, as well as the riparian land owners (most notably the Evans and Greenhills) and non-governmental entities such as the Nantucket Land Council. The modeling tools developed as part of this program provide the quantitative information necessary for the Town of Nantucket to develop and evaluate the most cost effective management alternatives to restore this coastal resource. Given this extensive prior data collection effort by the Town of Nantucket and its citizens, the MEP Technical Team conducted its analysis of Sesachacha Pond using Commonwealth matching funds at no additional cost to the Town.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The nutrients are primarily related to changes in watershed land-use associated with increasing population within the coastal zone over the past half century. Many of Massachusetts' embayments have nutrient levels that are approaching or are currently over this assimilative capacity, which begins to cause declines in their ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities and the food chain which they support. At higher levels, enhanced nitrogen loading from surrounding watersheds causes aesthetic degradation and inhibits even recreational uses of coastal waters. In addition to nutrient related ecological declines, an increasing number of embayments are being closed to swimming, shellfishing and other activities as a result of bacterial contamination. While bacterial contamination does not generally degrade the habitat, it restricts human uses. However like nutrients, bacterial contamination is frequently related to changes in land-use as watersheds become more developed. 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 the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within Southeastern Massachusetts alone, almost all of the municipalities (as is the case with the Town of Nantucket) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries.

Municipalities are seeking guidance on the assessment of nitrogen sensitive embayments, as well as available options for meeting nitrogen goals and approaches for restoring impaired systems. Many of the communities have encountered problems with "first generation" watershed based approaches, which do not incorporate estuarine processes. The appropriate method must be quantitative and directly link watershed and embayment nitrogen conditions. This "Linked" Modeling approach must also be readily calibrated, validated, and implemented to support planning. Although it may be technically complex to implement, results must be understandable to the regulatory community, town officials, and the general public.

The Massachusetts Estuaries Project represents the next generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (MA 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 for watershed-embayment management for communities throughout Southeastern Massachusetts.

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region's coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the DEP and municipalities with technical guidance to support policies on nitrogen management of their embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. The TMDL includes the role of nitrogen removal through tidal flushing, not just watershed nitrogen loading rates. In addition, each TMDL must contain an outline of an implementation plan. For this project, the DEP recognizes that there are likely to be multiple ways to achieve the desired goals, some of which are more cost effective than others and therefore, it is extremely important for each Town to further evaluate potential options suitable to their community. As such, DEP will likely be recommending that specific activities and timelines be further evaluated and developed by the Towns (sometimes jointly) through the Comprehensive Wastewater Management Planning process. However, it is absolutely clear that any remediation of the nitrogen related impairment presently within Sesachacha Pond must include an evaluation of periodic breaching.

In appropriate estuaries, TMDL's for bacterial contamination will also be conducted in concert with the nutrient effort (particularly if there is a 303d listing).   In these cases, the MEP (through SMAST) will produce a Technical Analysis and Report to support a bacterial TMDL for the system from which MA DEP develops the TMDL. The goal of the bacterial program is to provide information to guide targeted sampling for specific source identification and remediation.

In contrast to the bacterial program, the MEP nitrogen program also includes site-specific habitat assessments and watershed/embayment modeling approaches to develop and assess various nitrogen management alternatives for meeting selected nitrogen goals supportive of restoration/protection of embayment health.

The major MEP nitrogen management goals are to:

- provide technical analysis and supporting documentation to Towns as a basis for sound nutrient management decision making towards embayment restoration
- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment's model "alive" to address future municipal needs.

The core of the Massachusetts Estuaries Project analytical method is the Linked Watershed-Embayment Management Modeling Approach. This approach represents the "next

generation" of nitrogen management strategies. It fully links watershed inputs with embayment circulation and nitrogen characteristics.   The Linked Model builds on and refines 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 has been applied for watershed nitrogen management in approximately 15 embayments throughout Southeastern Massachusetts. In these applications it has become clear that 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.

The Linked Watershed-Embayment Model when properly parameterized, calibrated and validated for a given embayment becomes a nitrogen management planning tool, which fully supports TMDL analysis.   The Model facilitates the evaluation of nitrogen management alternatives relative to meeting water quality targets within a specific embayment. The Linked Watershed-Embayment Model also enables Towns to evaluate improvements in water quality relative to the associated cost.   In addition, once a model is fully functional it can be "kept alive" and updated for continuing changes in land-use or embayment characteristics (at minimal cost). 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.

Linked Watershed-Embayment Model Overview: The Model provides a quantitative approach for determining an embayment's: (1) nitrogen sensitivity, (2) nitrogen threshold loading levels (TMDL) and (3) response to changes in nitrogen loading rate or nitrogen removal through enhance tidal flushing. The approach is both calibrated and fully field validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-4).   This methodology integrates a variety of field data and models, specifically:

- Watercolumn Monitoring - multi-year embayment nutrient sampling
- Hydrodynamics -
    - embayment bathymetry
    - site specific tidal record
    - current records (in complex systems only)
    - hydrodynamic model
- Watershed Nitrogen Loading
    - watershed delineation

- stream flow (Q) and nitrogen load
- land-use analysis (GIS)
- watershed N model
- Embayment TMDL - Synthesis
    - linked Watershed-Embayment N Model
    - salinity surveys (for linked model validation)
    - rate of N recycling within embayment
    - D.O record
    - Macrophyte survey
    - Infaunal survey

I.2 SITE DESCRIPTION

Sesachacha Pond is a "simple" estuary, with a single basin and occasionally open tidal inlet. The open water area of 267 acres, makes Sesachacha Pond a great salt pond.   The Sesachacha Pond System presently exchanges tidal water only during periodic opening through the barrier beach, primarily as part of a management program and occasionally during major storms. Sesachacha Pond has been breached for management purposes for more than a century, with greater and lesser success. It is clear that the health of this estuary's habitats are dependent on the amount and timing of periodic tidal exchanges. For the MEP analysis, Sesachacha Pond is the principal estuarine basin in the modeling and thresholds analysis.

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 (Section VII). 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. As presented in a Sesachacha Pond 1989 Draft Environmental Impact Report (EIR), the barrier beach separating Sesachacha Pond from the Atlantic Ocean was breached once and sometimes twice per year as far back as the 1930's. This cycle of periodic openings continued generally uninterrupted up until 1981. The man-made breach to the pond was developed using the hydraulic gradient between the pond and the ocean to create a rapid outflow of pondwater to scour a channel in the barrier beach to a depth low enough to allow tidal exchange to occur for as long as possible (1-14 days). Infrequently the opening was reported to have stayed open for longer than two weeks. These periodic openings were undertaken as a means of controlling salinity in the pond in order to safe guard shellfish resources as well as allow for the passage of finfish into the pond, lower pond levels as a flood control measure, and allow nutrient rich waters to flush out of the pond as a water quality control measure. However, 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. It is clear that restoration of Sesachacha Pond will require evaluating the timing and duration of the periodic openings that would achieve the highest habitat quality within this system, relative to the logistical realities involved.

As management alternatives are being developed and evaluated, it is important to note that the Sesachacha Pond System is naturally a relatively dynamic system and has undergone significant alterations to its hydrologic and biological systems over the past 100 years. Within

such dynamic systems, restoration alternatives need to be evaluated relative to the system's "maximum level of sustainable environmental health" in addition to traditional standards.

While the nutrient related health of Sesachacha Pond as it exists today is linked to changes wrought by natural processes and human activities, it is the physical structure of the system laid down by the retreat of the Laurentide Ice Sheet that still controls much of the Systems' tolerance to nutrient inputs. The physical structure, shape and depth of a coastal embayment plays a major role in its susceptibility to ecological impacts from nutrient loading. Physical structure (geomorphology), which includes embayment bathymetry, isolation by the barrier beach and presence of saltwater reaches, when coupled with the tidal range of the adjacent open waters which helps drive the periodic flushing, all come together to define the dynamics of the system. System flushing rate is generally the primary factor for removing nutrients from active cycling within coastal bays and harbors. As a result maximizing system flushing is one of the standard approaches for controlling the nutrient related health of coastal embayments in general and Sesachacha Pond specifically.

The present configuration of the Sesachacha Pond system is relatively new in the coastal landscape, as the eastern coast of Nantucket Island is a dynamic region, where natural wave and tidal forces continue to reshape the shoreline (see Section V). All the while, Sesachacha Pond was formed by the flooding of a kettle pond as a result of rising sea level following the last glaciation, approximately 18,000 years BP.

While Sesachacha Pond presently has a relatively low nitrogen load from its watershed, due to its small size and proportionally large undeveloped areas, it is still significantly impaired by nitrogen enrichment. In addition, the proportionally large estuarine surface area results in a dominance of the external nitrogen loading being through direct atmospheric deposition to embayment waters. Even so, the total external nitrogen load to this great salt pond is low yet the system is eutrophic. This apparent paradox results from the low rate of annual tidal flushing which serves to greatly increase the nitrogen sensitivity of this system.

The inability of generate complete exchange of pond waters with normal breaching operations, has caused significant ecological degradation of the 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. It is clear that restoration of Sesachacha Pond will require addressing the management openings, especially as the system has historically operated as a salt pond and its proximity to the Atlantic Ocean prevents its management as a freshwater system due to periodic overwash of salt water (similar to Oyster Pond, Falmouth, and Rushy Marsh, Barnstable see MEP Technical Reports 2005, 2006).

Nitrogen Thresholds Analysis
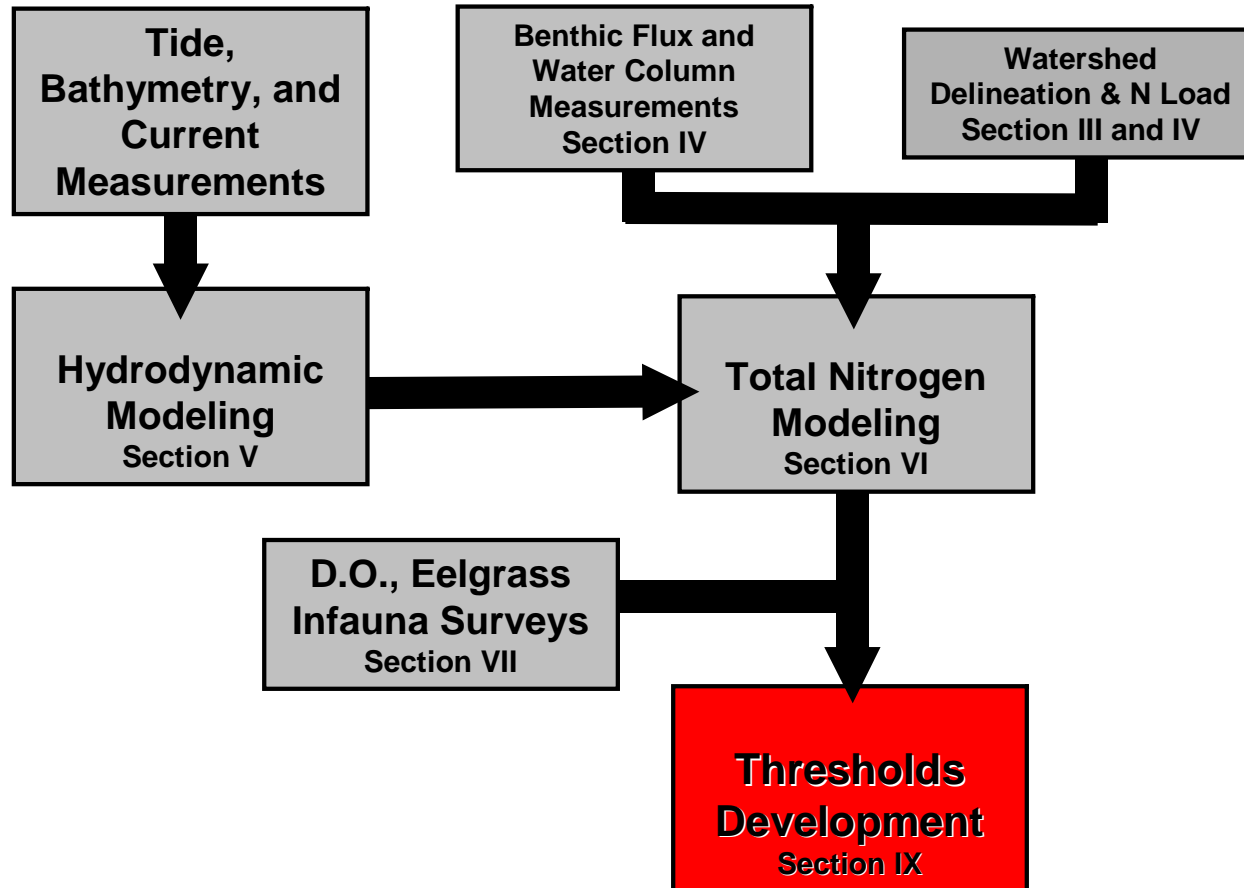
Figure I-4.   Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

I.3 NUTRIENT LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In sandy glacial outwash aquifers, such as in the watershed to the Sesachacha Pond System, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer minerals (Weiskel and Howes 1992). Since even Cape Cod, Nantucket and Martha's Vineyard "rivers" are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems on Cape Cod (DeSimone and Howes 1996, Weiskel and Howes 1992, Smith *et al.* 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). Though Sesachacha Pond is only occasionally opened to the ocean, the system as a "tidally restricted" coastal embayment presently follows this general pattern, where the primary nutrient of eutrophication in the system is nitrogen.

Nutrient 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 enclosed basins, shallow waters and large shoreline area, are generally the first indicators of nutrient pollution from terrestrial sources. By nature, these systems are highly productive environments, but nutrient over-enrichment of these systems worldwide is resulting in the loss of their aesthetic, economic and commercially valuable attributes.

Each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation. However, as loading increases a point is reached at which the capacity (termed assimilative capacity) is exceeded and nutrient related water quality degradation occurs. This point can be termed the "nutrient threshold" and in estuarine management this threshold sets the target nutrient level for restoration or protection. Because nearshore coastal salt ponds and embayments are the primary recipients of nutrients carried via surface and groundwater transport from terrestrial sources, it is clear that activities within the watershed, often miles from the water body itself, can have chronic and long lasting impacts on these fragile coastal environments.

Protection and restoration of coastal embayments from nitrogen overloading has resulted in a focus on determining the assimilative capacity of these aquatic systems for nitrogen. While this effort is ongoing (e.g. USEPA TMDL studies), southeastern Massachusetts has been the site of intensive efforts in this area (Eichner et al., 1998, Costa et al., 1992 and in press, Ramsey et al., 1995, Howes and Taylor, 1990, and the Falmouth Coastal Overlay Bylaw). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the "allowable N concentration increase" or "threshold nitrogen concentration" used in previous studies had a significant uncertainty due to the need for direct linkage of watershed and embayment models and site-specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout

the Sesachacha Pond System monitored by the Town of Nantucket Water Quality Monitoring Program, with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) utilized to refine the general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, Sesachacha Pond is presently beyond its ability to assimilate additional nutrients without further impairing the ecological health of this aquatic resource. This is in significant part due to the very restricted tidal exchange with Atlantic Ocean waters. Nitrogen levels are elevated, eelgrass beds have not been observed within Sesachacha Pond for the past half century or longer and there are large summer phytoplankton blooms and periodic hypoxia of bottom waters. The result is that nitrogen management of the Sesachacha Pond system is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed "eutrophication" and when the nutrient loading is primarily from human activities, "cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to the systems and contributed to the degradation in ecological health, it is possible in systems like Sesachacha Pond that eutrophication occurs with only minor influence of humankind, which must be considered in the nutrient threshold analysis. While this finding would not change the need for restoration, it would change the approach and potential targets for management. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a "pristine" system. In addition, to the impairment of Sesachacha Pond's sub-tidal habitats, there has been a loss of emergent salt marsh from the system stemming from the restricted tidal exchange in recent years.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important "boundary conditions" (e.g. watershed derived and offshore nutrient inputs) for water quality modeling of the Sesachacha Pond System; however, a thorough understanding of hydrodynamics is required to accurately determine nitrogen concentrations within each system. Therefore, water quality modeling of even periodically tidal estuaries must include a thorough evaluation of the hydrodynamics. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. The spread of pollutants may be analyzed from tidal current information developed by the numerical models. In the case of Sesachacha Pond, the hydrodynamic analysis is tailored to the fact that the pond is essentially a closed system for larger periods of the year with periodic openings that drive the circulation, mixing and exchange of pond waters with Atlantic Ocean water.

The MEP water quality evaluation examined the potential impacts of nitrogen loading into Sesachacha Pond under a variety of nitrogen input (loading) and hydrodynamic conditions (breaches of the barrier beach). A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents resulting from barrier beach breaching, groundwater inflow to the pond and water elevations (both actual and projected under various breaching scenarios) was employed. 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 models were 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, based upon watershed delineations and groundwater elevations (Section 3). Almost all nitrogen entering the Sesachacha Pond System is transported by freshwater, both through atmospheric deposition and through groundwater discharge. Concentrations of total nitrogen and salinity of Atlantic Ocean source waters and throughout Sesachacha Pond were taken from the Water Quality Monitoring Program (a coordinated effort between the Town of Nantucket, Coastal Systems Program at SMAST and others). Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of the Systems (2000-2005), coupled to long-term salinity records were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Sesachacha Pond System for the Town of Nantucket. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission, Town of Nantucket Planning Department and the Nantucket Land Council data. Offshore water column nitrogen values were derived from an analysis of monitoring stations in Nantucket Sound and the Atlantic Ocean (Section IV). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Section IV. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of the component sub-embayments was performed that included a review of existing water quality information and the results of a benthic analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of the Estuary in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined Bay threshold for restoration. This latter assessment represents only one of many solutions and is produced to assist the Town in developing a variety of alternative restoration options for this system. Finally, analyses of the Sesachacha Pond System were relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic idiosyncrasies of the pond and an examination of various breach options to improve nitrogen related water quality (and wetland communities). The results of the nitrogen modeling for each scenario have been presented (Section VIII).

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

Nutrient additions to aquatic systems cause shifts in a series of biological processes that can result in impaired nutrient related habitat quality. Effects include: 1) excessive plankton and macrophyte growth (which leads to reduced water clarity), 2) organic matter enrichment of waters and sediments, with the concomitant resulting increased rates of oxygen consumption and periodic depletion of dissolved oxygen, (especially in bottom waters), and 3) the limitation of the growth of desirable species such as eelgrass. Even without changes to water clarity and bottom water dissolved oxygen, the increased organic matter deposition to the sediments generally results in a decline in habitat quality for benthic infaunal communities (animals living in the sediments). This habitat change causes a shift in infaunal communities from high diversity deep burrowing forms (which include economically important species), to low diversity shallow dwelling organisms. This shift alone causes significant degradation of the resource and a loss of productivity to both the local shellfisherman and to the sport-fishery and offshore fin fishery, all of which are dependent upon these highly productive estuarine systems as a habitat and food resource during migration or during different life cycle phases. This process is generally termed "eutrophication" and in embayment systems, unlike in shallow lakes and pond, it is not a necessarily a part of the natural evolution of a system.

In most marine and estuarine systems, such as the Sesachacha Pond System, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. This approach has been formalized through the development of tools for predicting nitrogen loads from watersheds and the concentrations of water column nitrogen that may result. Additional development of the approach generated specific guidelines as to what is to be considered acceptable water column nitrogen concentrations to achieve desired water quality goals (e.g., see Cape Cod Commission 1991, 1998; Howes et al. 2003).

These tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. The present Massachusetts Estuaries Project (MEP) study focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Sesachacha Pond, a great salt pond. As the MEP approach requires substantial amounts of site specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of "data mining" and to gather additional information on an estuary's habitat quality or unique features.

Concern over the health of the Nantucket Island embayments have resulted in a number of studies relating to the nutrient related health of the Sesachacha Pond System over the past 2 decades. These investigations include both habitat assessments and studies relating to nitrogen loading, hydrology/hydrodynamics and habitat health. While the majority of the previous studies did not provide a holistic view of the Sesachacha Pond System, they provide useful information to the present MEP effort. One report in particular, the *Final Report on Nutrient Conditions in Sesachacha Pond,* was an initial attempt to evaluate this generally closed estuarine system and its watershed within the larger regional system and to evaluate the nutrient conditions/fluxes for watershed nitrogen inputs producing habitat declines within the receiving waters of the pond.

The initial nutrient study of Sesachacha Pond was undertaken by members of the MEP Technical Team while in residence at the Woods Hole Oceanographic Institution (Howes and Goehringer 1989). The study was conducted in 1988 and 1989 and was prepared for Aubrey Consulting Inc to provide the ecological management assessment related to the 1989 EIR. The goals of the 1988-1989 Sesachacha Pond nutrient study was to ascertain the current environmental health of the Sesechacha Pond ecosystem and to determine if the nutrient balance of the pond under various management options would allow for the establishment of a healthy and stable freshwater, or conversely, marine system. Healthy in this case was defined as an aquatic system absent of deleterious eutrophication or episodic anoxia, allowing the development of diverse and productive pelagic and benthic populations.

To ascertain the environmental conditions that existed in the pond at the time of the study measurements were made of water column, sediment and groundwater nutrient concentrations, sediment-water column nutrient flux and associated physical parameters under summer (maximum) and winter (minimum) levels of biological productivity. All of this data collection enabled the assessment of the environmental health of the pond to allow the prediction of the potential impacts of two specific management strategies; 1) the effects of reinstating an exchange with the ocean versus 2) continuation of diminishing surface exchange (generally only during storm related breaching) possibly to the point of preventing surface water flow under all conditions. Data collected under this initial Sesachacha Pond nutrient study was envisioned as serving in the development of a water quality baseline for any potential future monitoring effort undertaken to observe the response of the pond to any chosen course of management

Based on the work undertaken during this initial in depth investigation into the ecological function and nutrient cycling of Sesachacha Pond, specific conclusions were reached as follows:

Water Budget
1) Pondwater loss to the ocean through the barrier beach dune system (as groundwater) is large relative to the pond volume resulting in a relatively high transport rate. It was found that this could represent a major potential pathway for nutrient loss from the pond, when the pond level had reached equilibrium with the groundwater system (after 4-5 years of closure).

2) Between 1981 when the pond was last opened in the 1980's and 1984 when the first hydrologic measurements were made under the Perkins Jordan, Inc. investigation of the pond, water levels increased significantly due to groundwater inflow. During the period 1984 to 1988 water levels were determined to not be increasing in any significant manner thus enabling a hydrologic budget of the pond.

3) The freshwater inflow to the pond (1.42×10^9 L/yr) is large relative to the pond volume (65%) and is approximately equal to the increase in pond volume (1.4×10^9 L) from 1981 to the 1988-89 time frame when the nutrient study was conducted. This suggested that the time required to increase the water level within the pond once surface loss to the ocean ceases is short.

4) Inputs of freshwater through direct rainfall are on the same order as groundwater inputs, 1.1 versus 1.4×10^9 L/yr thereby suggesting that groundwater is less important to the water balance of the pond than was generally found at the time of the study.

Note that the total freshwater inflow estimated from this early study (2.5 x 10^6 m^3 y^{-1}) is consistent with the long-term freshwater inflow rates determined from the MEP watershed model (Chapter IV) and the short term rates based upon salinity dilution (Chapter VI).

<u>Nitrogen Balance</u>

5) Nitrogen was determined to be the nutrient limiting plant production in Sesachacha Pond as evidenced by water column data collected during the 1988-89 study. The major indication of nitrogen limitation came from both February and September water column data that showed that a DIN to PO_4^{3-} ratio of less than 1 existed in the pond. Values for the ratio of N to P less than 16 are generally indicative of nitrogen limitation.

6) The water column total nitrogen levels in the pond were very high (1.04-1.77 mg N/L) and were higher than values obtained in 1984 (0.46 mg N/L). Furthermore, the high TN values, low dissolved oxygen concentrations, low light penetration (Secchi depth = 1.1 meters), and high phytoplankton biomass in the water column supported the conclusion that Sesachacha Pond was a highly eutrophic system.

7) The input of nitrogen in rainfall and groundwater was of the same order of magnitude in 1988-89 as the loss in sediment accretion and groundwater effluent, but best estimates at the time indicated that inputs exceed outputs given the eutrophic state of the pond.

8) Loss of nutrients through groundwater flow to the ocean under the barrier beach accounted for approximately half of the outputs. Ultimately that meant that the pond did flush in a very limited way under a closed configuration and as such if the exchange is impeded in any way without providing for alternative transport of nutrients, then conditions in the pond would tend to worsen. However, the estimated rate of outflow depended upon the elevated pond levels that resulted after prolonged closure.

9) The removal of nutrients from the pond via groundwater outflow while a significant pathway for nutrient export is limited not just by flow rate, but by the fact that particulate N is retained in the pond. Subsequently, sediment remineralization of nitrogen provides 75 percent of the nitrogen to the water column therefore only a relatively small annual input of nitrogen to the pond is required to keep nutrient conditions high.

Based on the 1988-89 nutrient study of Sesachacha Pond the system was deemed eutrophic with episodic anoxia. Those conditions resulted in an unstable environment with low light penetration, high plant production and depauperate bottom communities. At the time of the study Sesachacha Pond required a mechanism to increase nutrient losses without which the pond conditions would worsen. Maintaining the pond as a saltwater system with continuous exchange with the ocean was seen as the best ecological solution as it would certainly lower nutrient levels in the pond and most likely result in the establishment of a productive marine ecosystem, however, the increased improvement over alternatives based on limited exchange was not deemed cost effective. A scenario based on maintaining the pond as a saltwater system with semi-annual exchange with ocean water was determined to be a sound management approach whereby nutrient export could be achieved via the increased exchange and salinity in the pond could be maintained above the 5 ppt threshold for shellfish growth and reproduction.

As a result of the 1988-89 nutrient study for Sesachacha Pond, an Environmental Notification Form (ENF) was submitted to the Massachusetts Environmental Policy Act (MEPA) Unit describing several pond management alternatives as follows:

- Status Quo – the pond would be left alone in its current (1988-89) state allowing nature to govern its condition
- Dune Restoration – dunes along the barrier beach would be rebuilt to reduce storm overwash and influence of salt spray
- Pond Opening – open the pond by dredging for a brief period of time as was done in the past (pre 1981)
- Connector Regulation – regulate a connector (one-way or two-way) between the pond and the ocean to maintain a specified range of salinity, water temperature and water level.

A Draft Environmental Impact Report (EIR) was developed by Aubrey Consulting Inc. whereby an analysis of Sesachacha Pond management alternatives (as described above) was presented in July 1989 under EOEA File Number 7452. The Draft EIR was prepared for the Massachusetts Audubon Society and was necessary prior to any pond opening or connector regulation. The technical work conducted in the development of the EIR resulted in a consensus being reached amongst representatives of a number of stakeholder groups (Massachusetts Audubon Society, Nantucket Land Council, Board of Selectman, Nantucket Conservation Commission, Quident-Squam Association, Shellfish Advisory Board and local residents) that would have the pond system managed as a brackish to marine aquatic environment. The EIR reflected the consensus reached amongst the various stakeholders and as such presented two specific management alternatives (periodic pond opening and two-way connector regulation) for maintaining Sesachacha Pond as a brackish environment.

Based on the results of the scientific study (discussed above) and associated data collection for the development of the EIR, an analysis of likely impacts for each management alternative was submitted to the MEPA Unit. Key points of the analysis of likely impacts include but are not limited to the fact that if the pond was left alone and no management of the pond was undertaken (status quo) the brackish pond would gradually revert to essentially a freshwater system as salt is diluted by groundwater inflow and precipitation. The pond would be slightly brackish due to over-washing events during storms and occasionally experience major perturbation as the barrier beach is naturally breached during extreme events such as a hurricane. As a result of the general freshening of the system the wetlands associated with the Sesachacha Pond system will transition from brackish to freshwater wetlands with consequent die-off of brackish wetland causing high carbon/nutrient loading to the pond. Additional die-off of freshwater wetlands could occur during natural breaches of the barrier beach during extreme events thus further increasing the carbon and nutrient load to the pond. As a result of increasing nutrient loads to the pond and limited flushing of the system it was concluded in the Draft EIR that plankton would proliferate during periods of the year when blooms tend to occur thereby driving oxygen levels in the pond even lower with resultant effects on existing flora and fauna. Freshening of the pond system would preclude the establishment or maintenance of any saltwater shellfish populations and more frequent periods of anoxia would preclude the existence of a healthy benthic infaunal community (be it freshwater or saltwater organisms). As regards the nutrient conditions of the pond under a status quo scenario, it was determined that nutrient levels in the pond would continue to increase as inputs remained the same or increased over time with potential development and no sinks or avenues for increased export of nutrient load would exist. The pond system would remain eutrophic as much of the annual load of

nutrients to the pond remains in the pond in a particulate form while some of the nutrient pool (dissolved nutrients) is exported with groundwater flow to the ocean.

Of specific interest to the MEP were the findings in the draft EIR which related to the management alternative (periodic pond opening) that was essentially adopted through the 1990's to present. Up until 1981 the barrier beach was artificially breached once to twice per year using a bulldozer and the inlet remained open naturally for a temporary amount of time as a result of natural daily tidal flow in and out of the pond. Long shore transport would then fill the breach in over 1-14 days and the pond would remain closed until the next time it was determined the pond should be opened to the ocean. From a biological point of view, periodic opening of the pond system would result in a more saltwater dominated marsh system with the distribution of species such as cattails, *Panicum* and *Phragmites* being limited to higher elevation areas of low salinity in the vicinity of groundwater seepage into the pond. With regards to phytoplankton the influx of saltwater and the exchange of nutrient rich pond water with nutrient poor ocean water would drive nutrient concentrations in the pond to a lower level and as such produce an aquatic environment less supportive of major plankton blooms. That is not to say that blooms would not occur, but rather, that bloom events may be less frequent and less intense. The flushing of nutrients out of the pond and exchange with "clean" ocean water would allow the salinity to be sustained at levels supportive of marine shellfish species while also reducing the incidence of low dissolved oxygen events.

Considering the current (2006) state of Sesachacha Pond in light of the analysis of likely impacts presented in the Draft EIR (1989) for the pond opening management scenario, certain 1989 findings were shown to be reasonable while others did not manifest themselves. Despite the periodic opening of Sesachacha Pond, the aquatic system remains extremely eutrophic with very high chlorophyll levels, extremely poor water clarity and very low dissolved oxygen. The ecological state of Sesachacha Pond remains impaired as evidenced by data collected by the MEP (Section VII) and as a result the MEP analytical approach has been invoked to refine the management of the Sesachacha Pond system to drive further restoration of this aquatic resource.

As part of the Town of Nantucket's management of Sesachacha Pond, the Marine and Coastal Resource Department and Health Department established a water quality monitoring program to track salinity, nutrient related parameters and bacterial indicators. In the development of the MEP Nutrient Threshold Report for the Sesachacha Pond system, the MEP Technical Team incorporated into its analysis of nutrient conditions in Sesachacha Pond all water quality results generated by this program. This data also supported the MEP Technical Report that served as the basis for the MassDEP's TMDL development related to bacterial contamination of Sesachacha Pond.

In addition to its focus on nutrient related habitat quality and developing a nitrogen management approach for Sesachacha Pond, the MEP was tasked with the development of a Bacteria Technical Report to serve as the basis for the MassDEP development of a bacteria TMDL for Sesachacha Pond (as noted above). The technical report was submitted to the MassDEP in January of 2006 and is currently under review. A well developed database of historical bacteria data was available for the development of the technical report for Sesachacha pond. The bacterial data used for the MEP bacteria analysis of the system were generated exclusively by the Massachusetts Division of Marine Fisheries as well as the Town of Nantucket Marine and Health Departments. Based on previous discussions with the MassDEP, the technical report was not meant to direct the reader to specific bacterial sources (point or non-point), nor was it intended to produce Fecal Coliform Waste Load Allocations (WLAs) or Load

Allocations by bacteria source for the Sesachacha Pond system. The reported aimed to point to likely geographic sections of the overall Sesachacha Pond system that are the most likely source of the highest bacterial concentrations recorded to date. Historical data was compiled from multiple agencies and was synthesized in the context of land use distributions as provided to the Massachusetts Estuaries Project (MEP) by the Nantucket Land Council. In order to identify likely sections of Sesachacha Pond responsible for highest bacterial contamination, geometric means and percent exceedances were developed for historical data obtained for the report.   In the present effort, the MEP Technical Team is focusing on restoring the resources of Sesachacha Pond and in the bacterial report, focused on the ability to utilize the resources of the Pond (swimming and shellfishing) post-restoration.

Sesachacha Pond is currently classified as Prohibited. It is currently used only as a seed grow out area from which mature seed are transplanted to clean areas. Based upon the MEP Bacterial Technical Report, most of the bacteria data for Sesachacha Pond were collected from 1985 through 1995 with Town data available for 2000-2003.   Summer exceedances of the geometric mean of the water quality standard of 14 cfu/100ml range from approximately 26% to approximately 64% at the stations sampled. Exceedances of the water quality standard of 43 cfu/100ml range from approximately 20% to approximately 43%. Winter exceedances of the water quality standard of 14 CFU/100 mls by the geometric mean are 0% at all stations sampled except for Station 2 which has an exceedance of 17%. More than 10% of the samples exceeded the water quality standard of 43 cfu/100ml only at Station 2. Summer wet/dry data from the Town of Nantucket showed a wet geometric mean approximately 3 times the dry mean, although neither mean exceeded the water quality standard of 14. More than 10% of the wet samples only exceeded the water quality standard of 43 cfu/100ml.

Sesachacha Pond clearly exhibited bacterial contamination from 1985 to 1991 and based on recent data of the Nantucket Health Department, there is potential contamination currently. Waterfowl is a potential source of bacteria inputs but buildup of bacteria in the pond may be significant because of a lack of flushing of the pond which is limited to the few times during the year when the barrier beach is dredged to create a temporary inlet to allow exchange with oceanic water.

Overall, the DMF and Town of Nantucket datasets suggest waterfowl and/or wildlife as the most likely sources to Sesachacha Pond, although potential runoff along the southwestern shore may also be a contributory factor. This conclusion is based upon:

- observation of higher bacterial levels in summer than winter (biological activity)
- association with rain events (wetland and possible runoff)
- spatial distribution of contamination, highest in southwestern station adjacent undeveloped watershed area and wetlands (to northwest)

Although the bacterial levels are highest in the southwestern station, it is possible that the contamination is also associated with the wetlands entering along the northwestern shore where there is not sampling data. Given the low levels of bacterial contamination within the Pond and the above factors, it appears that sampling associated with summer rain events, with refined spatial coverage would help to address the source issue.

The land-uses along the southwestern shore of Sesachacha Pond indicate "natural" sources of bacteria, as the land is currently undeveloped and protected. However, the open space and wetlands almost certainly support populations of waterfowl and wildlife that would be more prevalent during the summer months when higher bacterial contamination is evident.   In

addition, rain events tend to help transfer bacterial loads from emergent wetlands to adjacent Pond waters.

- The limited number of potential bacterial sources and the availability of existing data allows for generation of a bacterial TMDL using existing water quality data. At present, the data suggests wildlife and/or waterfowl as major bacterial sources to pond waters. Additional sources include runoff, with septic systems being less likely. A sanitary survey approach which provides a refined spatial sampling of summer time wet/dry weather fecal bacteria and includes assessments of the wetland area (culvert under Polpis Rd) and the waters off Quidnet should be considered. In addition, targeted assessment of (a) bacterial levels at the culvert under Polpis Road and the southwestern wetlands under wet and dry weather conditions and (b)potentially "failed" septic systems within Quidnet (BOH).

Sesachacha Pond is a eutrophic pond exhibiting very high nutrient levels, low dissolved oxygen and intermittently bacterial levels exceeding the standards for shellfishing. The Town of Nantucket, from whom most of the bacteria data was acquired, has demonstrated through water quality testing pre and post breaching that the pond must remain open for sufficient duration during regular breechings in order to flush the stagnant biological matter from the system and allow for a return to a salt water based ecological system.

Sustained low level bacterial levels within Sesachacha Pond indicate a relatively small but continuous source of contamination to surface waters. Among the sources of contamination which have been frequently identified as contributing to embayments within southeastern Massachusetts, waterfowl and wildlife (and possibly road runoff) are the most likely.   The sustained low level bacteria concentrations are probably the result of a combination of factors:

Likely contributors
1. waterfowl (likely)
2. drainage from the wetland southwest of the pond (likely)

Possible contributors
3. wildlife throughout the protected open space portions of the watershed (possible)
4. road runoff primarily from Polpis Rd. (possible)

Unlikely contributors
5. septic systems close to the pond (unlikely – due to distribution))
6. swimmers in the summer months (unlikely)
7. point-source discharge (none identified)

The lack of flushing allows bacteria to flourish in the nutrient enriched environment created from many of the same sources. It appears that solving the problem of nutrient enrichment will also address the bacterial issue to some degree since sources of the two contaminants are in many cases the same. We recommend that the work listed above in "Recommendations for a Bacterial TMDL Program" be incorporated as recommendations into a future TMDL report being ever mindful that the pending nutrient TMDL will also include more detailed suggestions for the improvement of overall water quality.

As regards bacterial contamination in Sesachacha Pond, the Massachusetts Estuaries Project recommended that Sesachacha Pond be designated for further study to collect more recent data with which to evaluate the pond's status regarding the nature and sources of

bacterial inputs. It was not recommended that it be added to the 303d list at this time due to limited development in the watershed and the preponderance of Protected Open Space potentially supportive of large waterfowl and wildlife populations.

The common focus of the Town of Nantucket Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments of the Island (including Sesachacha Pond) to support evaluations of observed water quality and habitat health. This multi-year effort was initiated in 1992, with significant support from the Nantucket Marine and Health Departments and the Nantucket Land Council. It has been continued by the Town of Nantucket through 2005. The Nantucket Water Quality Monitoring Program in Sesachacha Pond developed a data set at four sampling stations (Figure II-1) that elucidated the long-term water quality of the pond system.

Results of water quality sampling conducted by the Town of Nantucket are presented by the Town Biologist in a series of annual reports. Annual reports from 1992-2005 were provided to the MEP Technical Team. In general, all the annual reports reviewed did present valuable data on physical parameters at each station within Sesachacha Pond including: temperature, salinity, secchi depth and total depth. Additionally, data are presented on dissolved oxygen, pH, nutrients (nitrate, phosphorous and ammonia) and in some instances bacteria (fecal coliform). Annual report also provided a record of pond openings and duration of opening with earlier reports (1992, 1993 and 1994) also providing a summary of plankton tows and benthic surveys conducted at the established sampling stations. While these plankton and benthic surveys do not continue on in later years to the same level of detail as was found in the earlier reports, the later reports do provide data intermittently on the state of shellfish resources at specific locations in the pond system. Moreover, the later reports provided the morphometry of Sesachacha Pond as it relates specifically to surface areas of the pond as a function of changing depth as well as associated pond volumes. Collectively, all the annual reports represent an extremely valuable record of conditions in Sesachacha Pond as a function of time and the periodic openings of the pond system to the ocean and essential information on the number and duration of pond openings over the past decade.

The MEP effort builds upon the Town's Water Quality Monitoring Program, previous hydrodynamic/hydrologic evaluations conducted during the development of the Draft EIR and water quality analyses conducted by SMAST.   The Town of Nantucket Water Quality Monitoring Program provided the quantitative water column nitrogen data (2000-2005) required for the implementation of the MEP's Linked Watershed-Embayment Approach. The MEP effort also builds upon previous watershed delineation and land-use analyses and the embayment water quality and eelgrass/macrophyte surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Sesachacha Pond embayment system.   The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the Sesachacha Pond system and to reduce costs to the Town of Nantucket. Additionally, as remediation plans for this and other various systems are implemented, the continued monitoring important to provide quantitative information to the Town relative to the efficacy of remediation efforts.
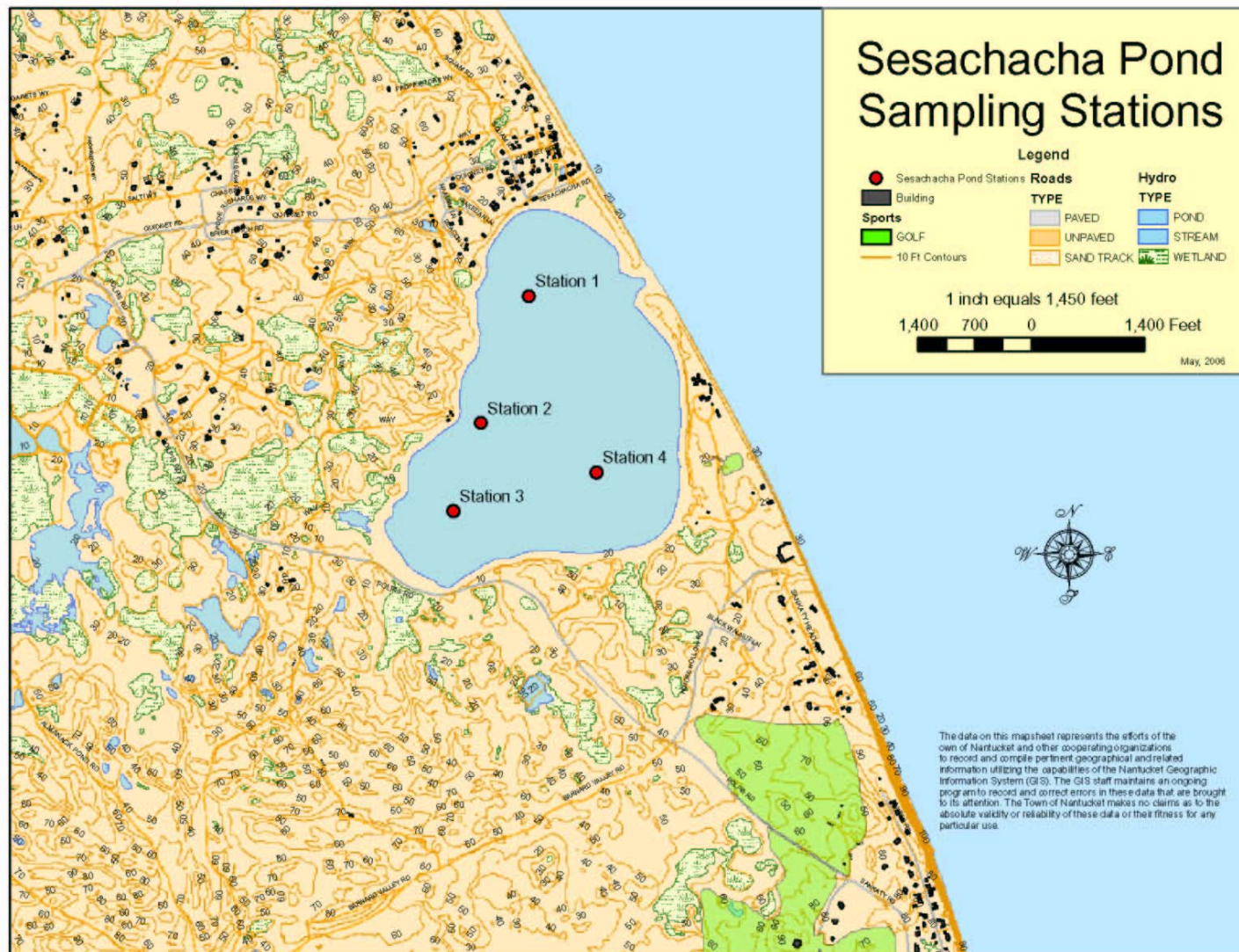
Figure II-1.   Town of Nantucket Water Quality Monitoring Program sampling stations for Sesachacha Pond as provided by the Town of Nantucket Marine Department.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

Nantucket Island is located near the southern edge of late Wisconsinan glaciation (Oldale and Barlow, 1986). As such, the geology of the island is largely composed of outwash plain and moraine with reworking of these deposits by the ocean that has occurred since the retreat of the glaciers. The moraine, which is located relatively close to Nantucket Harbor, consists of unsorted sand, clay, silt, and gravel, while the outwash, which tends to be located toward the southern half of the main portion of the island is composed of stratified sands and gravel deposited by glacial melt water. The groundwater system of Nantucket Island is generally characterized by a shallow, unconfined aquifer and a separate deep, confined aquifer, although some recent deep well drillings have suggested that there are additional confining units of undetermined extent that are interlaced in the unconfined layer (Lurbano, 2001). These characterizations of the geology, including the installation of numerous long-term monitoring wells, by the US Geological Survey over the last few decades have provided the basis for subsequent activities, including the delineation of estuary watersheds. The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS).

During the development of the Nantucket Water Resources Management Plan, an island-wide groundwater mapping project, using many of the USGS wells, was completed to characterize the water table configuration (Horsley, Witten and Hegeman Inc., 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 a watershed delineation for Sesachacha Pond (Figure III-1); this watershed delineation has been largely confirmed by subsequent water table characterizations (*e.g.*, Lurbano, 2001, Gardner and Vogel, 2005).

III.2 SESACHACHA POND CONTRIBUTORY AREAS

MEP staff also compared the HWH Pond watershed to a 2004 aerial base map to see if any shoreline changes would require watershed alterations. This comparison found that this watershed delineation is still appropriate and, therefore, it is adopted as the MEP watershed and is used in the watershed analysis. There are no subwatersheds.

Based on the watershed areas and a recharge rate of 27.25 inches per year, a groundwater discharge volume was determined for Sesachacha Pond; this volume was used to assist in the salinity calibration of the tidal hydrodynamic models. The recharge rate was developed based on calibration of the Cape Cod groundwater models prepared by the USGS and used to delineate estuary watersheds for the MEP (Walter and Whealan, 2005). This recharge rate is also consistent with the upper portion of a range of calculated recharge on Nantucket based on tritium measurements (Knott and Olimpio, 1986). The overall estimated groundwater flow into Sesachacha Pond from the MEP watershed is 7,961 m3/d.
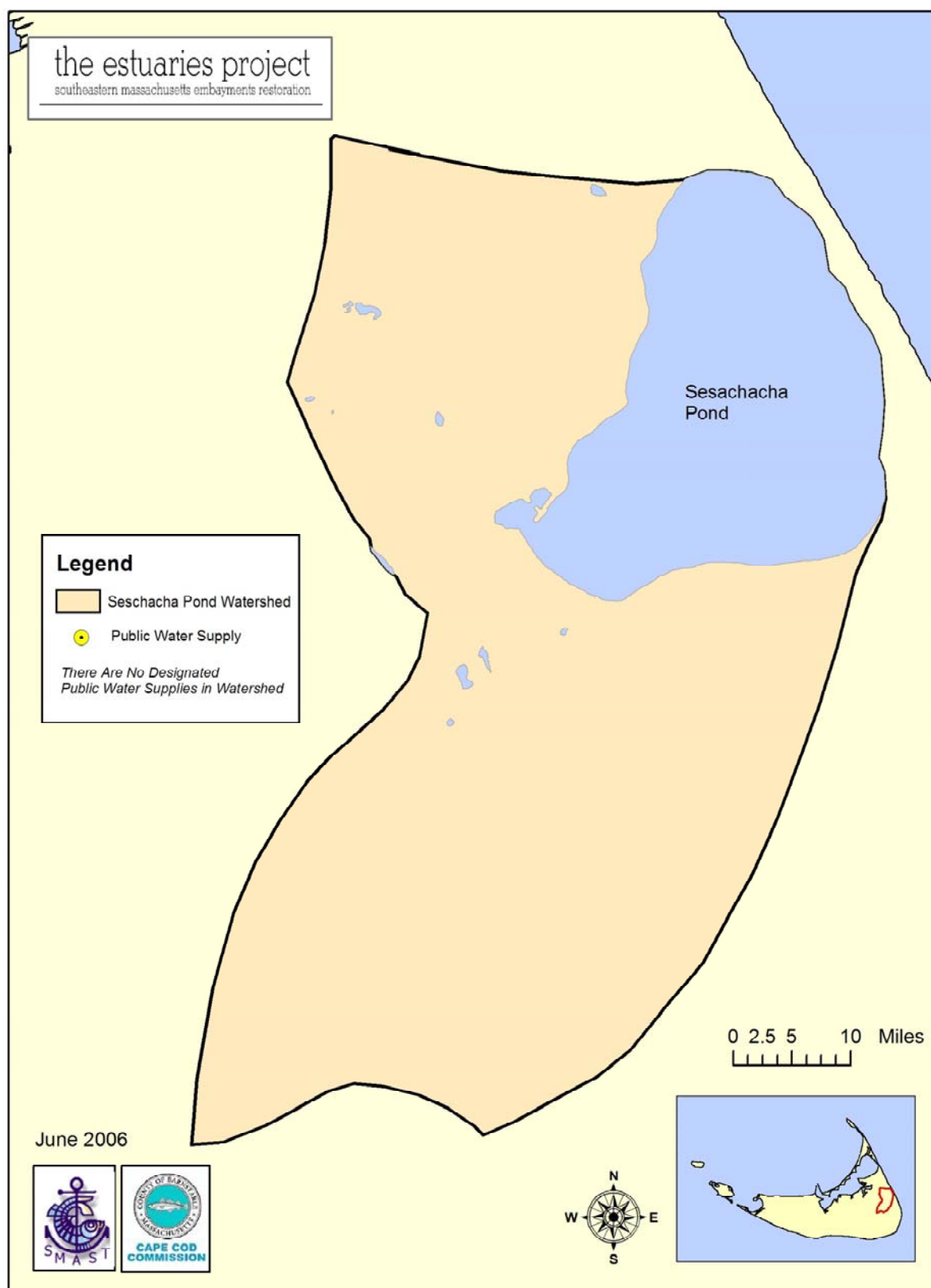
Figure III-1.   Watershed delineations for the Sesachacha estuary system..

Review of watershed delineations for Sesachacha Pond allows new hydrologic data to be evaluated and the watershed delineation to be reassessed. The evaluation of older data and incorporation of new data during the development of the MEP watershed model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model used for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon the land-uses that are included/excluded within the contributing areas. Small errors in watershed area can result in large errors in loading if a large source is counted in or out. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the downgradient estuary. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the aquatic systems and ultimately to the estuarine waters of the Sesachacha Pond system (Section V.1).

IV. WATERSHED NITROGEN LOADING TO EMBAYMENT: LAND USE, STREAM INPUTS, AND SEDIMENT NITROGEN RECYCLING

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

Management of nutrient related water quality and habitat health in coastal waters requires determination of the amount of nitrogen transported by freshwaters (surface water flow, groundwater flow) from the surrounding watershed to the receiving embayment of interest. In southeastern Massachusetts and the Islands, the nutrient of management concern for estuarine systems is nitrogen and this is true for the Sesachacha Pond system. Determination of watershed nitrogen inputs to these embayment systems requires the (a) identification and quantification of the nutrient sources and their loading rates to the land or aquifer, (b) confirmation that a groundwater transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes. This latter natural attenuation process results from biological processes that naturally occur within ecosystems. Failure to account for attenuation of nitrogen during transport results in an over-estimate of nitrogen inputs to an estuary and an underestimate of the sensitivity of a system to new inputs (or removals). In addition to the nitrogen transport from land to sea, the amount of direct atmospheric deposition on each embayment surface must be determined as well as the amount of nitrogen recycling within the embayment, specifically nitrogen regeneration from sediments. Sediment nitrogen recycling results primarily from the settling and decay of phytoplankton and macroalgae (and eelgrass when present). During decay, organic nitrogen is transformed to inorganic forms, which may be released to the overlying waters or lost to denitrification within the sediments. Burial of nitrogen is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source of nitrogen to embayment waters or in some cases a sink for nitrogen reaching the bottom. Failure to include the nitrogen balance of estuarine sediments generally leads to errors in predicting water quality, particularly in determination of summertime nitrogen load to embayment waters.

The MEP Technical Team includes technical staff from the Cape Cod Commission (CCC). In coordination with other MEP Technical Team members, CCC staff developed nitrogen-loading rates (Section IV.1) from the watershed to the Sesachacha Pond embayment system (Section III). The Sesachacha Pond watershed does not contain any subdivisions for inland freshwater systems or sub-embayments.

In order to determine nitrogen loads from the watershed, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other detailed studies is applied to other portions. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon watershed-specific land uses and pre-determined nitrogen loading rates. For the Sesachacha Pond embayment system, the model used Town of Nantucket land-use data transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as average town water use). Determination of the nitrogen loads required obtaining watershed-specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection

effort of the MEP. However, the watershed to Sesachacha Pond contains only smaller aquatic features that do not have separate watersheds delineated and, thus they are not explicitly included in the attenuation component of the watershed analysis. If these small features were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (~10%) overestimated given the distribution of nitrogen sources and these features within the watershed. Internal nitrogen recycling was also determined throughout the tidal reaches of the Sesachacha Pond Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Estuaries Project staff obtained digital parcel and tax assessors data from the Town of Nantucket Geographic Information Systems Department. Digital parcels and land use/assessors data are from 2005. These land use databases contain traditional information regarding land use classifications (MADOR, 2002) plus additional information developed by the town. The parcel data and assessors' databases were combined for the MEP analysis by using the Cape Cod Commission Geographic Information System (GIS).

Figure IV-1 shows the land uses within the Sesachacha Pond estuary watershed area. Land uses in the study area are grouped into four land use categories: 1) residential, 2) undeveloped, 3) agricultural, and 4) public service/government, including road rights-of-way. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2002). "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (e.g., wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges.

In the overall Sesachacha Pond System watershed, the predominant land use based on area is public service (i.e., government owned lands, roads, and rights-of-way), which accounts for 85% of the watershed area; residential is the second highest percentage area of the system watershed (6%) as presented in Figure IV-2. However, residential and public service parcels are both 39% (or 31) of the total 80 parcels in the system watershed. Seventeen of the 31 residential parcels are single-family residences (MADOR land use code 101), while 14 are multifamily residences (MADOR land use code 109). Undeveloped parcels are the third highest parcel count (18%) in the watershed after residential and public service. Overall, undeveloped land uses account for 4% of the entire Sesachacha Pond watershed area. There are no commercial or industrial properties in the watershed area.
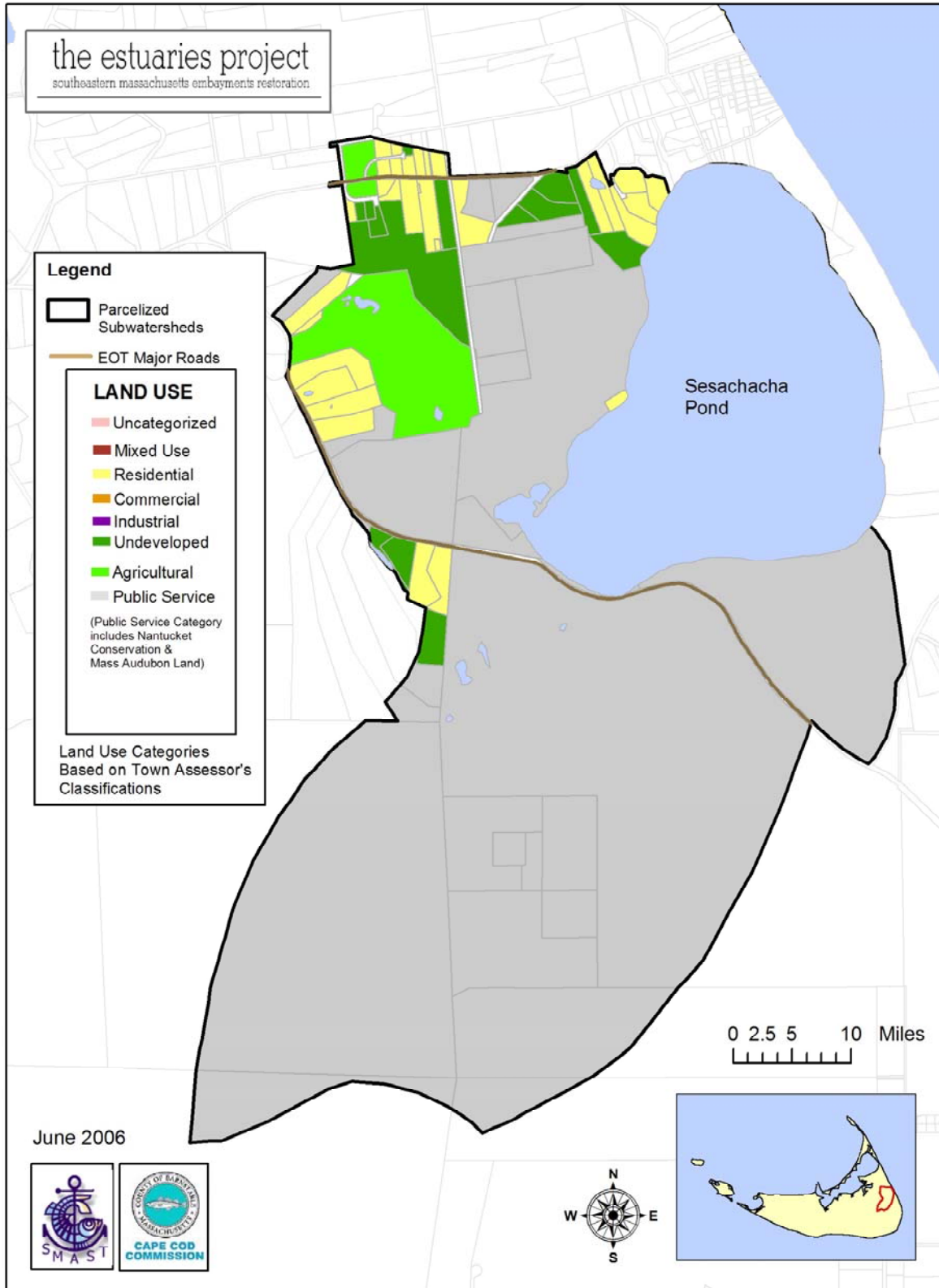
Figure IV-1.   Land-use in the Sesachacha Pond watershed. The watershed is completely contained within the Town of Nantucket. Land use classifications are based on assessors' records provided by the town.

In order to estimate wastewater flows, MEP staff generally work with municipal or water supplier partners in the study watershed to obtain parcel-by-parcel water use information. As such, the Cape Cod Commission staff contacted Mark Willette of the Wannacomet Water Company (WWC). At the time of the request, the WWC was in the process of developing parcel-by-parcel water use information, but would not have it developed in time to complete the MEP analysis. Mr. Willette graciously offered to review 2005 water use records of approximately 130 residential accounts in order to develop an appropriate average residential water use flow. This review found the average residence used 1,703 cubic feet per year with a range among the reviewed accounts of 108 to 5,150 cubic feet per year. The average water use translates into 12,738 gallons per year or 35 gallons per day; this average was used as a proxy for residential wastewater generation in the Sesachacha Pond watershed. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon this average water-use and a combined nitrogen concentration/consumptive use of water factor (see Section IV.1.2).
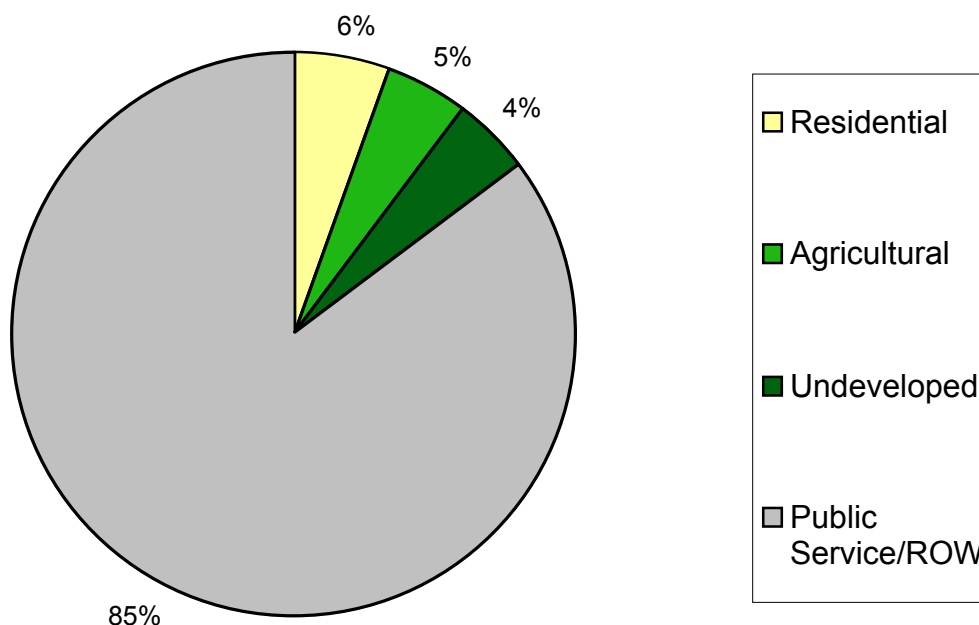
Figure IV-2.   Distribution of land-uses by area within the watershed to Sesachacha Pond.

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

The Massachusetts Estuaries Project septic system nitrogen loading rate is fundamentally based upon a per capita nitrogen load to the receiving aquatic system. Specifically, the MEP septic system wastewater nitrogen loading is based upon a number of studies and additional information that directly measured septic system and per capita loads on Cape Cod or in similar geologic settings (Nelson et al. 1990, Weiskel & Howes 1991, 1992, Koppelman 1978, Frimpter et al. 1990, Brawley et al. 2000, Howes and Ramsey 2000, Costa et al. 2001). Variation in per

capita nitrogen load has been found to be relatively small, with average annual per capita nitrogen loads generally between 1.9 to 2.3 kg person-yr^{-1}.

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts, decennial census data yields accurate estimates of total population only in selected watersheds. To correct for this uncertainty and more accurately assess current nitrogen loads, the MEP employs a water-use approach. The water-use approach is generally applied on a parcel-by-parcel basis within a watershed, where annual or annualized water meter data is linked to assessors parcel information using GIS techniques. The parcel specific water use data is converted to septic system nitrogen discharges (to the receiving aquatic systems) by adjusting for consumptive use (e.g. irrigation) and applying a wastewater nitrogen concentration. The water use approach focuses on the nitrogen load, which reaches the aquatic receptors downgradient in the aquifer.

All nitrogen losses within the septic system are incorporated into the MEP analysis. For example, information developed at the MASSDEP Alternative Septic System Test Center at the Massachusetts Military Reservation on Title 5 septic systems have shown nitrogen removals between 21% and 25%. Multi-year monitoring from the Test Center has revealed that nitrogen removal within the septic tank was small (1% to 3%), with most (20 to 22%) of the removal occurring within five feet of the soil adsorption system (Costa et al. 2001). Downgradient studies of septic system plumes indicate that further nitrogen loss during aquifer transport is negligible (Robertson et al. 1991, DeSimone and Howes 1996).

In its application of the water-use approach to septic system nitrogen loads, the MEP has ascertained that while the per capita septic load is well constrained by direct studies for the Estuaries Project region, the consumptive use and nitrogen concentration data are less certain. As a result, the MEP has derived a combined term the effective N Loading Coefficient (consumptive use times N concentration) of 23.63, to convert water (per volume) to nitrogen load (N mass). This coefficient uses a per capita nitrogen load of 2.1 kg N person-yr^{-1} and is based upon direct measurements and corrects for changes in concentration that result from per capita shifts in water-use (e.g. due to installing low plumbing fixtures or high versus low irrigation usage).

The nitrogen loads developed using this approach have been validated in a number of long and short term field studies where integrated measurements of nitrogen discharge from watersheds could be directly measured. Weiskel and Howes (1991, 1992) conducted a detailed watershed/stream tube study that monitored septic systems, leaching fields and the transport of the nitrogen in groundwater to adjacent Buttermilk Bay. This monitoring resulted in estimated annual per capita nitrogen loads of 2.17 kg (as published) to 2.04 kg (if new attenuation information is included). Modeled and measured nitrogen loads were determined for a small sub-watershed to Mashapaquit Creek in West Falmouth Harbor (Smith and Howes, manuscript in review) where measured nitrogen discharge from the aquifer was within 5% of the modeled N load. Another evaluation was conducted by surveying nitrogen discharge to the Mashpee River in reaches with swept sand channels and in winter when nitrogen attenuation is minimal. The modeled and observed loads showed a difference of less than 8%, easily attributable to the low rate of attenuation expected at that time of year in this type of ecological situation (Samimy and Howes, unpublished data).

While census based population data has limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water used based on average residential occupancy to measured average water uses. This is performed as a quality

assurance check to increase certainty in the final results. This comparison has shown that the larger the watershed the better the match between average water use and occupancy. For example, in the cases of the combined Great Pond, Green Pond and Bournes Pond watershed in the Town of Falmouth and the Popponesset Bay/Eastern Waquoit Bay watershed, which covers large areas and have significant year-round populations, the septic nitrogen loading based upon the census data is within 5% of that from the water use approach. This comparison matches some of the variability seen in census data itself. Census blocks, which are generally smaller areas of any given town, have shown up to a 13% difference in average occupancy form town-wide occupancy rates. These analyses provide additional support for the use of the water use approach in the MEP study region.

Overall, the MEP water use approach for determining septic system nitrogen loads has been both calibrated and validated in a variety of watershed settings. The approach: (a) is consistent with a suite of studies on per capita nitrogen loads from septic systems in sandy outwash aquifers; (b) has been validated in studies of the MEP Watershed "Module", where there has been excellent agreement between the nitrogen load predicted and that observed in direct field measurements corrected to other MEP Nitrogen Loading Coefficients (e.g., stormwater, lawn fertilization); (c) the MEP septic nitrogen loading coefficient agrees in specific studies of consumptive water use and nitrogen attenuation between the septic tank and the discharge site; and (d) the watershed module provides estimates of nitrogen attenuation by freshwater systems that are consistent with a variety of ecological studies. It should be noted that while points b-d support the use of the MEP Septic N Coefficient, they were not used in its development. The MEP Technical Team has developed the septic system nitrogen load over many years, and the general agreement among the number of supporting studies has greatly enhanced the certainty of this critical watershed nitrogen loading term.

The independent validation of the water quality model (Section VI) adds additional weight to the nitrogen loading coefficients used in the MEP analyses and a variety of other MEP embayments. While the MEP septic system nitrogen load is the best estimate possible, to the extent that it may underestimate the nitrogen load from this source reaching receiving waters provides a safety factor relative to other higher loads that are generally used in regulatory situations. The lower concentration results in slightly higher amounts of nitrogen mitigation (estimated at 1% to 5%)) needed to lower embayment nitrogen levels to a nitrogen target (e.g. nitrogen threshold, cf. Section VIII). The additional nitrogen removal is not proportional to the septic system nitrogen level, but is related to the how the septic system nitrogen mass compares to the nitrogen loads from all other sources that reach the estuary (i.e. attenuated loads).

In order to provide an independent validation of the average residential water use within the Sesachacha Pond System watershed, MEP staff reviewed US Census population values for the Town of Nantucket. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. Based on data collected during the 2000 US Census, average occupancy within Nantucket is 2.57 people per occupied housing unit, while year-round occupancy of available housing units is 40%. If the average occupancy is multiplied by 55 gpd, the average water use for occupied units is 142 gpd. However, because the majority of the residential units on Nantucket are not occupied, the average occupancy of all units is 1.03 people per house and if this is multiplied by the regulatory 55 gpd flow per person, the average water use drops to 57 gpd. This flow is still higher than the average determined from the water use review, but it

suggests that the water use average is reasonable given the high percentage of seasonally occupied dwellings.

In most previously completed MEP studies, average population and average water use have generally agreed fairly well. Since the Sesachacha Pond analysis is dependent on a water use average rather than parcel-by-parcel water use, MEP staff also reviewed more refined US Census information and 1990 Census information. Besides reviewing data on town and state levels, the US Census also develops information for smaller areas (i.e., tracts and block groups). Sesachacha Pond is contained in one census tract: Tract 9505. Year 2000 Census residential occupancy rate in Tract 9505 is 2.26 people per house, while the average occupancy of all units is 0.53. Percentage of occupied housing units is 22%. The 1990 tract delineation is not the same area as the 2000 tract, but the averages tend to be similar to those from 2000.

It is clear from this analysis that the average occupancy in the Sesachacha Pond watershed is lower than the town-wide average. If the average occupancy of all units is multiplied by the regulatory 55 gpd per person, the average water use in Tract 9505 is 29 gpd. The 35 gpd average flow determined from a review of WWC accounts approximates this population-based flow and this analysis suggests that the average water use flow is an appropriate basis for determining residential wastewater nitrogen loads within the Sesachacha Pond watershed. Since there are no commercial or industrial water uses in the watershed, the residential water use estimate is the basis for all wastewater nitrogen generated in the Sesachacha watershed.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized residential lawns, golf courses, and cranberry bogs, with lawns being the predominant source within this category. In order to add this source to the nitrogen-loading model for the Sesachacha Pond system, MEP staff reviewed available information about residential lawn fertilizing practices. No golf courses, cranberry bogs, or turf areas other than residential lawns were identified within the watershed.

Residential lawn fertilizer use has rarely been directly measured in watershed-based nitrogen loading investigations. Instead, lawn fertilizer nitrogen loads have been estimated based upon a number of assumptions: a) each household applies fertilizer, b) cumulative annual applications are 3 pounds per 1,000 sq. ft., c) each lawn is 5000 sq. ft., and d) only 25% of the nitrogen applied reaches the groundwater (leaching rate). Because many of these assumptions had not been rigorously reviewed in over a decade, the MEP Technical Staff undertook an assessment of lawn fertilizer application rates and a review of leaching rates for inclusion in the Watershed Nitrogen Loading Sub-Model.

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. The assessment accounted for proximity to fresh ponds and embayments. Based upon ~300 interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sq. ft., 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a leaching rate of 20% results in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors are used in the MEP nitrogen loading calculations. It is likely that this still represents a conservative estimate of nitrogen load from residential lawns. It should be

noted that professionally maintained lawns were found to have the higher rate of fertilizer application and hence higher estimated loss to groundwater of 3 lb/lawn/yr.

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the Cape Cod Commission's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and Massachusetts DEP's Nitrogen Loading Computer Model Guidance (1999). The recharge rate for natural areas and lawn areas is the same as developed in the MEP-USGS groundwater modeling effort on Cape Cod and, which appears to be reasonable for Nantucket (Section III). Factors used in the MEP nitrogen loading analysis for the Sesachacha Pond watershed are summarized in Table IV-1.

Table IV-1.	Primary Nitrogen Loading Factors used in the Sesachacha Pond MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Barnstable data. *Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.			
Nitrogen Concentrations:		mg/l	Recharge Rates:	in/yr
Road Run-off		1.5	Impervious Surfaces	40
Roof Run-off		0.75	Natural and Lawn Areas	27.25
Direct Precipitation on Embayments and Ponds		1.09	Water Use/Wastewater:	
Natural Area Recharge		0.072		
Wastewater Coefficient		23.63		
Fertilizers:			Existing developed residential parcels and buildout residential parcels:	35 gpd
Average Residential Lawn Size (ft^2)*		5,000		
Residential Watershed Nitrogen Rate (lbs/lawn)*		1.08		

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, parcels were assigned to the watershed based initially on whether at least 50% or more of the land area of each parcel was located within the watershed. Following the assigning of boundary parcels, all large parcels were examined individually and were split (as appropriate) in order to obtain less than a 2% difference between the total land area of the watershed and the sum of the area of the parcels within the watershed. The resulting "parcelized" watershed to Sesachacha Pond is shown in Figure IV-3.
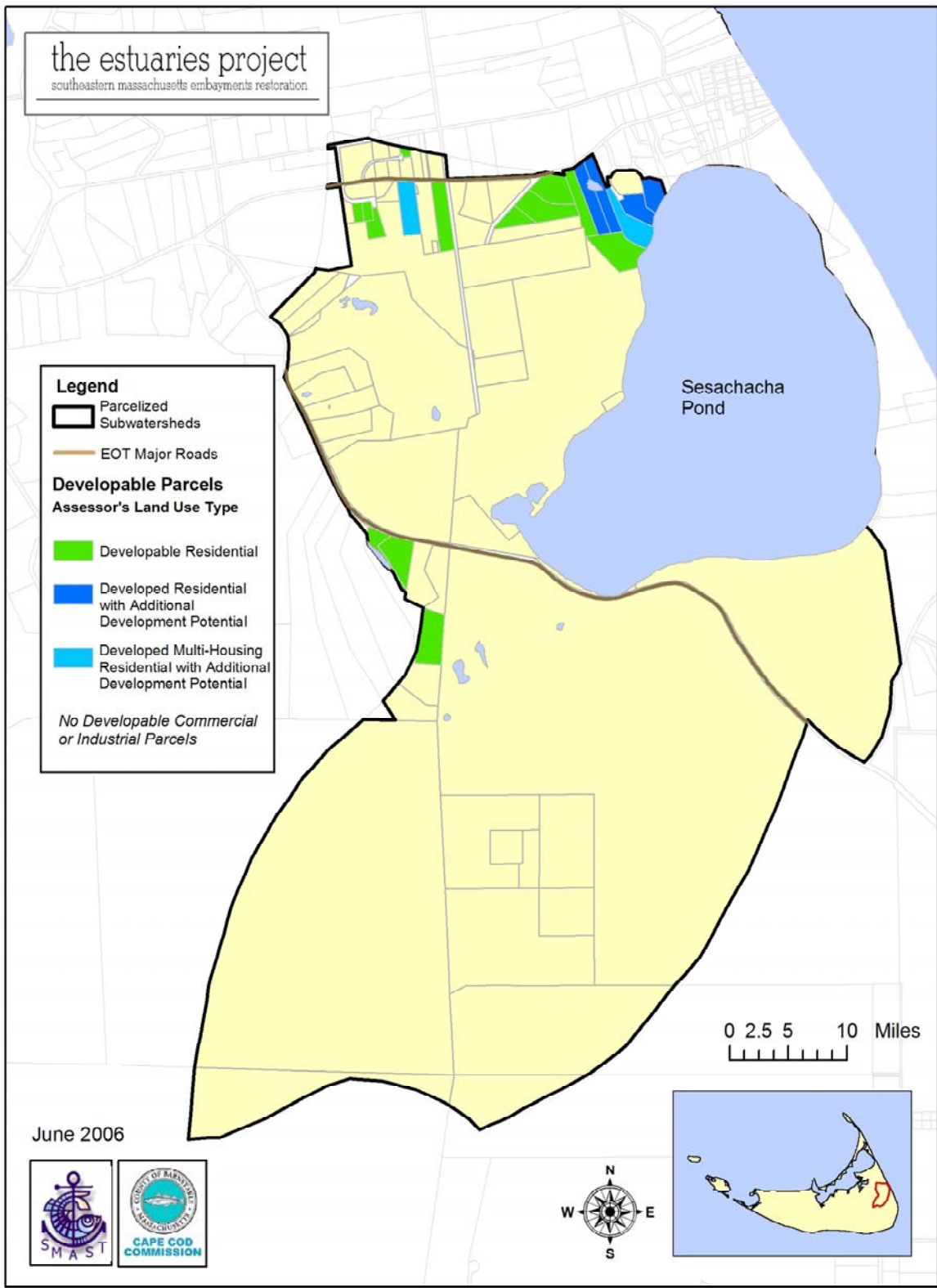
Figure IV-3.   Parcels, Parcelized Watersheds, and Developable Parcels in the Sesachacha Pond watershed.

The review of individual parcels straddling the watershed boundary included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the Sesachacha Pond estuary. The assignment effort was undertaken to better define the loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives. Following the assignment of all parcels, a watershed module was generated summarizing water use, parcel area, frequency, and road area. This module was then integrated with nitrogen loading calculations to create the Sesachacha Pond Watershed Nitrogen Loading module of the Linked Watershed-Embayment Model's water quality component.

For management purposes, the watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Sesachacha Pond System, the major types of nitrogen loads are: wastewater (e.g., septic systems), fertilizer, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the watershed by each source category (Figure IV-4).

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development within the study area watershed. For the Sesachacha Pond modeling, MEP staff consulted with Town of Nantucket planners (Andrew Vorce, personal communication) and Nantucket Land Council (Cormac Collier, personal communication) to determine the factors that would be used in the assessment. MEP staff developed the buildout by reviewing the development potential of each property. The buildout procedure used in this watershed and generally completed by MEP staff is to evaluate town zoning to determine minimum lot sizes in each of the zoning districts, including overlay districts (*e.g.*, water resource protection districts). Larger lots are subdivided by the minimum lot size to determine the total number of new lots and existing developed properties are reviewed for additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence. MEP staff also included additional development on residential parcels that are classified as developable residential (state class land use codes 130 and 131) but are less than the minimum lot size and are greater than 5,000 square feet. These parcels are assigned one residence in the buildout; 5,000 square feet is a common minimum buildable lot size in town regulations. Properties classified by the Nantucket assessor as "undevelopable" (e.g., codes 132, 392, and 442) were not assigned any development at buildout. Following the initial buildout review, MEP staff reviewed the findings with local officials identified above and adjusted the buildout for individual parcels accordingly. Buildout loads are developed based on the factors shown in Table IV-1. All the parcels included in the buildout assessment of the Sesachacha Pond watershed are shown in Figure IV-3.

Overall, a nitrogen load for each additional residence is included in the cumulative unattenuated buildout indicated in a separate column in Table IV-2. Buildout additions within the Sesachacha Pond watershed in either scenario will increase the unattenuated loading rate by 3%.

Table IV-2.   Sesachacha Pond Nitrogen Loads. All values are kg N yr^{-1}.

Name Watershed ID#	Sesachacha Pond N Loads by Input (kg/y):						Present N Loads			Buildout N Loads		
	Wastewater	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Sesachacha Pond	36	15	93	1137	210	48	1492		1492	1540		1540
Sesachacha Pond	36	15	93	0	210	48	355		355	403		403
Sesachacha Estuary surface deposition				1137			1137		1137	1137		1137

Overall Load
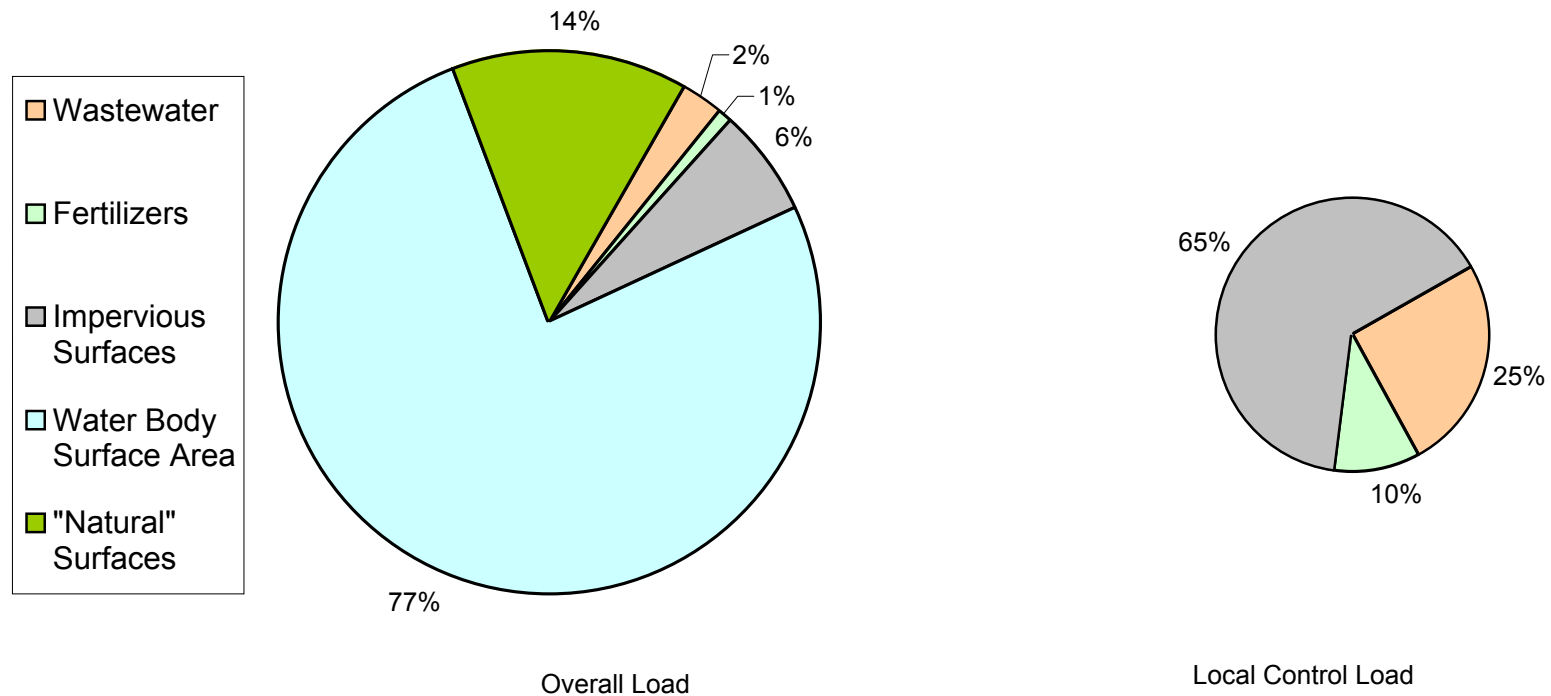
Local Control Load

Figure IV-4.   Land use-specific unattenuated nitrogen load (by percent) to the Sesachacha Pond System watershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

IV.2.1 Background and Purpose

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed.   This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out or sewering analysis) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the watershed of the Sesachacha Pond System were based upon the delineated watershed (Section III) and its land-use coverages (Section IV.1). If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters.   This condition exists in watersheds where nitrogen transport is through groundwater in sandy outwash aquifers. The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. This is the case for the Sesachacha Pond watershed. Unlike most watersheds in southeastern Massachusetts, nitrogen does not pass through a surface water ecosystem on its path to the adjacent embayment or in this case brackish/salt pond system. It is in these surface water systems that the needed conditions for nitrogen retention and denitrification exist. As there were no streams or great fresh ponds within the Sesachacha Pond watershed, the watershed loading approach considered that nitrogen reaching the water table was transported without attenuation in the groundwater system until discharge to the estuary.

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the Benthic Nutrient Flux Surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters within each major basin area within the Nantucket Harbor embayment system. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters.   These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

As stated in above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system.   Nitrogen enters the Sesachacha Pond embayment system predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters.   If all of the nitrogen remained within the watercolumn (once it entered), then predicting watercolumn nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate.   This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton "particles". Most of these "particles" remain in the water column for sufficient time to be flushed out to a downgradient larger water body (like the Atlantic Ocean when Sesachacha Pond is opened). However, as is the case in Sesachacha Pond, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited

on the bottom. In long residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with their associated nitrogen "load" become incorporated into the surficial sediments of the aquatic system.

In general the fraction of the phytoplankton population which enters the surficial sediments of a shallow embayment and salt pond: (1) increases with decreased hydrodynamic flushing, (2) increases in low velocity settings, (3) increases within enclosed tributary basins, particularly if they are deeper than the adjacent embayment. To some extent, the settling characteristics can be evaluated by observation of the grain-size and organic content of sediments within an estuary.

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment watercolumn for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with deep depositional basins or salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer. Failure to account for the nitrogen balance of the sediments generally results in significant errors in determination of threshold nitrogen loadings. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

In the specific case of Sesachacha Pond, which only has periodic tidal exchange (on the order of 25 days per year), the importance of nitrogen cycling in the sediments becomes a larger part of the nitrogen balance than in fully tidal systems. Also, the closed basin of Sesachacha Pond allows for both the standard MEP core incubation method to determine sediment nitrogen release and a second integrated system approach that MEP has employed in other closed basins. This latter approach uses a mass balance of nitrogen within the basin and the watershed model to estimate average system-wide nitrogen release (Section IV.3.3).

IV.3.2 Method for determining sediment-watercolumn nitrogen exchange

For the Sesachacha Pond system, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected from 8 sites in Sesachacha Pond (August 2002) and incubated using a temporary field laboratory set up at the University of Massachusetts – Boston, Nantucket Field Station. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior

to incubation. The number of core samples from each site (see Figure IV-5) per incubation were as follows:

Sesachacha Pond Benthic Nutrient Regeneration Cores

- Station Sesa-1   1 core   (Upper Region; shallow)
- Station Sesa-2   1 core   (Upper Region; deep)
- Station Sesa-3   1 core   (Middle-upper Region; shallow)
- Station Sesa-4   1 core   (Middle-upper Region; deep)
- Station Sesa-5   1 core   (Middle-lower Region; deep)
- Station Sesa-6   1 core   (Middle-lower Region; deep)
- Station Sesa-7   1 core   (Lower Region; shallow)
- Station Sesa-8   1 core   (Lower Region; shallow)

Sampling was distributed throughout the salt pond system and the results for each site combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

Sediment-watercolumn exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1998) for nutrients and metabolism. Upon return to the field laboratory temporarily set up adjacent the Harbor, the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and ortho-phosphate (Murphy and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-20°C) for assay of nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON (D'Elia *et al.* 1977). Rates were determined from linear regression of analyte concentrations through time.

Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA. The laboratory follows standard methods for saltwater analysis and sediment geochemistry.
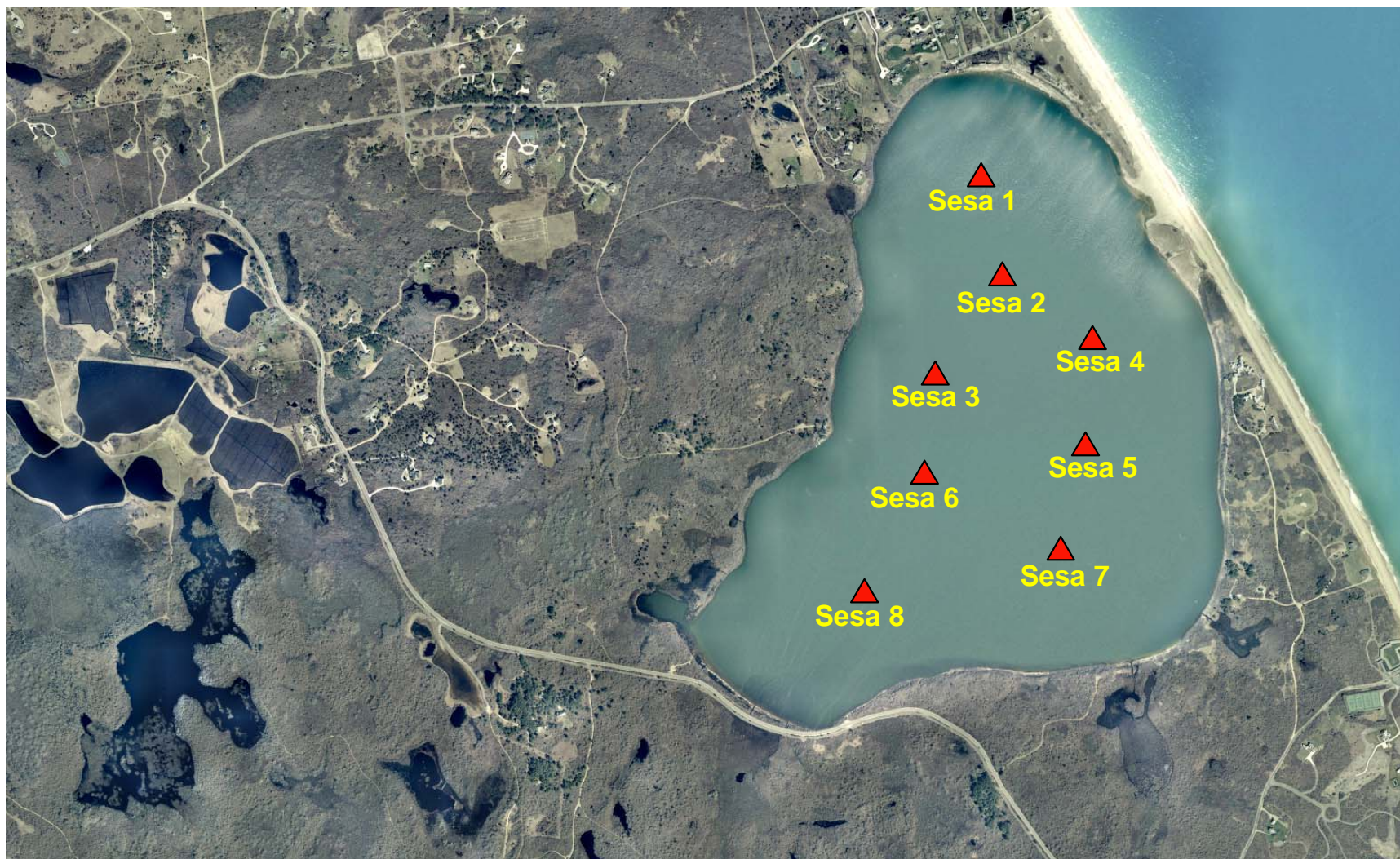
Figure IV-5.   Sesachacha Pond embayment system sediment sampling sites (red symbols) for determination of nitrogen regeneration rates. Numbers are for reference to Table IV-3.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

Water column nitrogen levels are the balance of inputs from direct sources (land, rain etc), losses (denitrification, burial), regeneration (water column and benthic), and uptake (e.g. photosynthesis). As stated above, during the warmer summer months the sediments of shallow embayments typically act as a net source of nitrogen to the overlying waters and help to stimulate eutrophication in organic rich systems. However, some sediments may be net sinks for nitrogen, particularly in the deep depositional basins of eutrophic systems, and some may be in "balance" (organic N particle settling = nitrogen release). Sediments may also take up dissolved nitrate directly from the water column and convert it to dinitrogen gas (termed "denitrification"), hence effectively removing it from the ecosystem. This process is typically a small component of sediment denitrification in embayment sediments, since the water column nitrogen pool is typically dominated by organic forms of nitrogen, with very low nitrate concentrations. However, this process can be very effective in removing nitrogen loads in some systems, particularly in streams, ponds and salt marshes, where overlying waters support high nitrate levels.

In addition to nitrogen cycling, there are ecological consequences to habitat quality of organic matter settling and mineralization within sediments, these relate primarily to sediment and water column oxygen status. However, for the modeling of nitrogen within an embayment it is the relative balance of nitrogen input from water column to sediment versus regeneration which is critical. Similarly, it is the net balance of nitrogen fluxes between water column and sediments during the modeling period that must be quantified. For example, a net input to the sediments represents an effective lowering of the nitrogen loading to down-gradient systems and net output from the sediments represents an additional load.

The relative balance of nitrogen fluxes ("in" versus "out" of sediments) is dominated by the rate of particulate settling (in), the rate of denitrification of nitrate from overlying water (in), and regeneration (out). The rate of denitrification is controlled by the organic levels within the sediment (oxic/anoxic) and the concentration of nitrate in the overlying water. Organic rich sediment systems with high overlying nitrate frequently show large net nitrogen uptake throughout the summer months, even though organic nitrogen is being mineralized and released to the overlying water as well. The rate of nitrate uptake, simply dominates the overall sediment nitrogen cycle.

In order to model the nitrogen distribution within an embayment it is important to be able to account for the net nitrogen flux from the sediments within each part of each system. This requires that an estimate of the particulate input and nitrate uptake be obtained for comparison to the rate of nitrogen release. Only sediments with a net release of nitrogen contribute a true additional nitrogen load to the overlying waters, while those with a net input to the sediments serve as an "in embayment" attenuation mechanism for nitrogen.

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is

during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-6).

Unfortunately, the tendency for net release of nitrogen during warmer periods, coincides with the periods of lowest nutrient related water quality within temperate embayments. This sediment nitrogen release is in part responsible for poor summer nutrient related health. Other major factors causing the seasonal water quality decline are the lower solubility of oxygen during summer, the higher oxygen demand by marine communities, and environmental conditions supportive of high phytoplankton growth rates.

In order to determine the net nitrogen flux between water column and sediments, all of the above factors were taken into account. The net input or release of nitrogen within a specific embayment was determined based upon the measured total dissolved nitrogen uptake or release, and estimate of particulate nitrogen input.
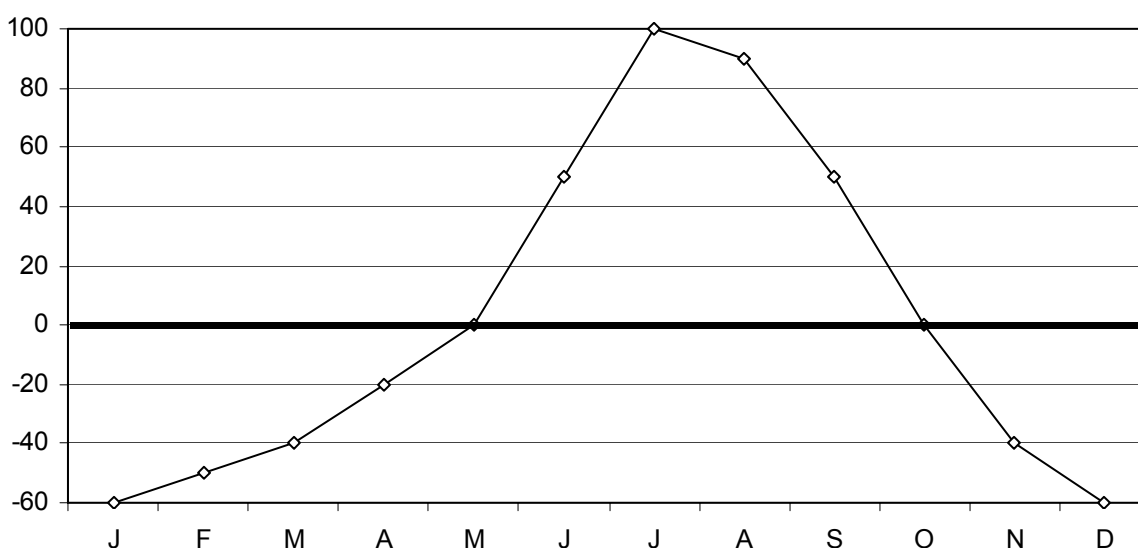
Figure IV-6.   Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Sediment Nitrogen Release by Standard Core Approach: Sediment sampling was conducted within the shallow and deeper basins of the Sesachacha Pond system in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. As expected flow velocities are very small in Sesachacha Pond. These data were then used to determine the nitrogen balance within the embayment.

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment

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site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (Chapter V). Based upon the low velocities, a water column particle residence time of 8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins), but given vertical mixing considerations a longer residence time was used for the deep basin sediments, (half the shallow settling rate was used). Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas which are net nitrogen sinks for the aquatic system. This approach has been previously validated in outer Cape Cod embayments (Town of Chatham embayments) by examining the relative fraction of the sediment carbon turnover (total sediment metabolism) which would be accounted for by daily particulate carbon settling. This analysis indicated that sediment metabolism in the highly organic rich sediments of the wetlands and depositional basins is driven primarily by stored organic matter (ca. 90%). Also, in the more open lower portions of larger embayments, storage appears to be low and a large proportion of the daily carbon requirement in summer is met by particle settling (approximately 33% to 67%). This range of values and their distribution is consistent with ecological theory and field data from shallow embayments. Additional, validation has been conducted on deep enclosed basins (with little freshwater inflow), where the fluxes can be determined by multiple methods. In this case the rate of sediment regeneration determined from incubations was comparable to that determined from whole system balance.

Net nitrogen release rates for use in the water quality modeling effort for Sesachacha Pond (Chapter VI) are presented in Table IV-3. The general pattern is consistent with other estuaries. The depositional basin showed a slight uptake of nitrogen, similar to other comparably configured basins. The measured rates of nitrogen release or uptake from the sediments within Sesachacha Pond were also comparable to other similar embayments with similar configuration and flushing rates. Overall, sediment nitrogen showed a clear pattern of net release in the shallow depths (<4.5 m) which make up most of the pond bottom, and net uptake in the deep holes (4.5-6 m). The rate of release in the shallow areas was 49.2 mg N m^{-1} d^{-1}, compared with other systems investigated by the MEP which ranged from 79.5 mg N m^{-1} d^{-1} in Meetinghouse Pond to 34.2 mg N m^{-1} d^{-1} in the lower reach of The River (Upper Pleasant Bay). Similarly, the rates fell within the wide range found for the Vineyard Sound, Popponesset Bay Estuary, which ranged from 85 mg N m^{-1} d^{-1} to - 17 mg N m^{-2} d^{-1}. The deeper region (~15% of basin area) showed a net uptake of nitrogen, -36.2 mg N m^{-1} d^{-1}, on the same order as other eutrophic depositional area like Muddy Creek (-16 mg N m^{-1} d^{-1}) and mesotrophic, but similarly configured, Eel Pond in Bourne (-9 mg N m^{-1} d^{-1}).

Table IV-3.	Rates of net nitrogen return from sediments to the overlying waters of Sesachacha Pond. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July -August rates. N = number of sites			
	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			
Location	**Mean**	**S.E.**	**N**	**i.d.**
Sesachacha Pond				
Shallow	49.2	6.8	4	Sesa 1,3,7,8
Deep	-36.3	2.3	4	Sesa 2,4,5,6
Station numbers refer to Figures IV-5.				

System-wide Sediment Nitrogen Release

In a closed basin, such as Sesachacha Pond, it is possible to determine the system-wide rate of nitrogen return from the bottom sediments based upon time series water column total nitrogen data and the rate of external nitrogen loading (watershed + atmosphere). In the case of Sesachacha Pond the external loading rate is relatively small (4.09 kg N d^{-1}, see Chapter IV). This increases the potential sensitivity of using a nitrogen mass balance approach to determine sediment nitrogen flux.

Water column average total nitrogen levels were available from the Town of Nantucket Water Quality Monitoring Program for 2004 and 2005. Note that there is no horizontal gradient across the pond (Chapter VI). The data was collected about monthly through a period when the Pond was not open to the ocean. The linear increase in total nitrogen concentration during both years is directly related to the rate of net nitrogen release from the sediments, integrated over the entire pond. This rate of nitrogen increase in pond waters was used to calculate a rate of nitrogen increase per square meter across the entire pond per day, from the water volume and bottom area measurements (Chapter V, VI) as shown in Figure IV-7. The rate of increase observed in the water column was 21.7 g m^{-2} d^{-1}. However, the temporal rise in nitrogen concentration also includes inputs from the watershed and atmosphere, in addition to release of nitrogen from the sediments. Correcting for these external nitrogen inputs, using daily average rates, results in an estimated daily input from the sediments during summer of 18.0 mg N $m^{-2}d^{-1}$. This sediment nitrogen release rate compares very well with the area weighted average (accounting for shallow versus deep sediments) determined from the sediment cores of 21.2 mg N $m^{-2}d^{-1}$. Given this agreement and the system-wide integration of the mass balance approach, 18.0 mg N $m^{-2}d^{-1}$ was used in the nitrogen water quality modeling (Chapter VI).
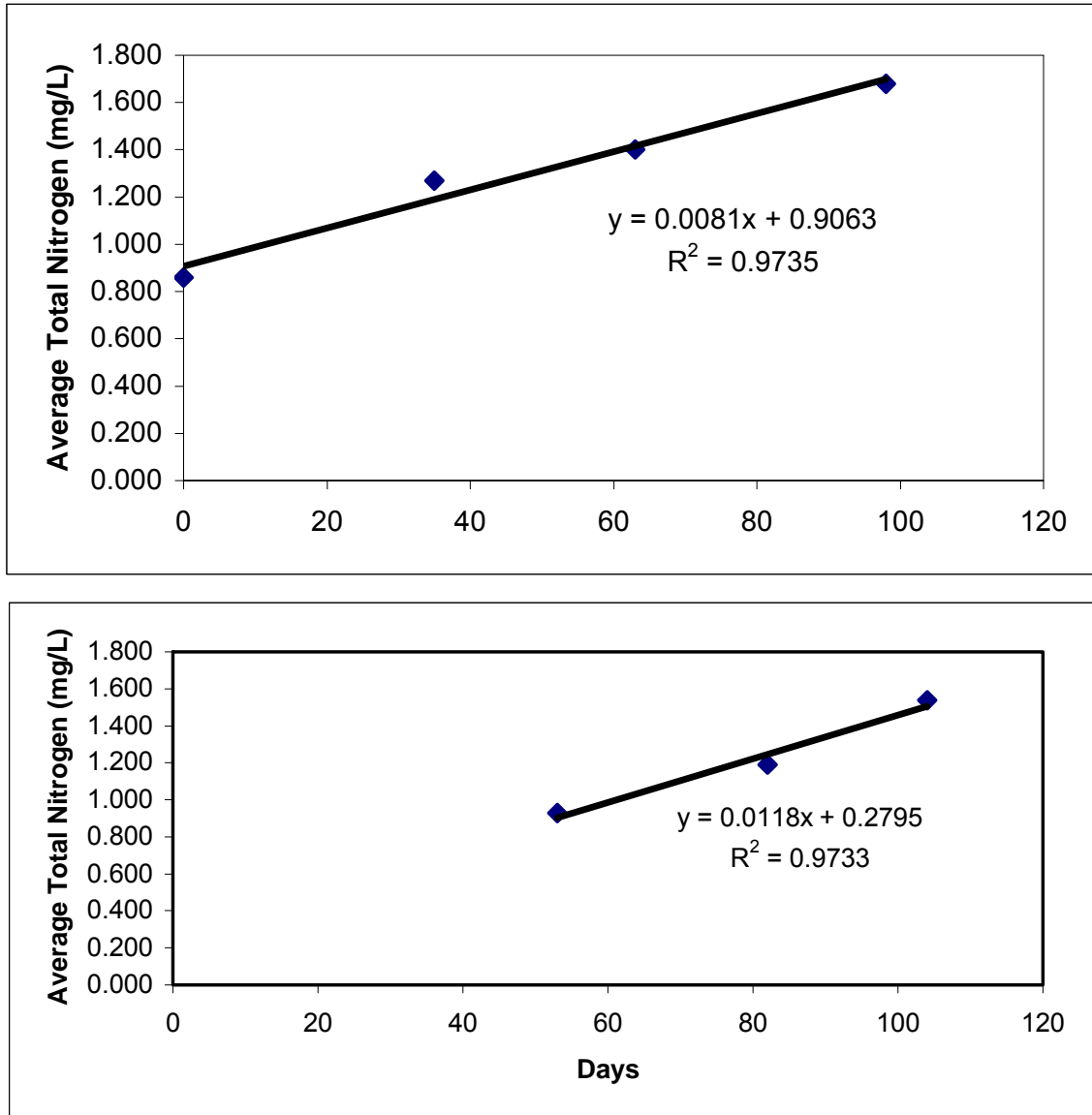
Figure IV-7.   Time course of average total nitrogen concentrations in Sesachacha Pond during non-open periods in summers of 2004 (top) and 2005 (bottom). The linear increase in total nitrogen is directly proportional to duration of pond closure.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes field data collection effort and the development of hydrodynamic models for the Sesachacha Pond system (Figure V-1). For this system, the model offers an understanding of water movement from the pond during a breach, and provides the first step towards evaluating water quality, as well as a tool for later determining nitrogen loading "thresholds". Nutrient loading data combined with measured environmental parameters within the system become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing water quality parameters, as well as determining the likely positive impacts of various alternatives for improving health of the pond, facilitating the understanding how pollutant loadings into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

In general, water quality studies of tidally influenced estuaries must include 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. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. For example, the spread of pollutants may be analyzed from tidal current information developed by the numerical models.

Coastal ponds like Sesachacha are the initial recipients of freshwater flows (i.e., groundwater and surfacewater) and the nutrients they carry. An embayment's shape influences the time that nutrients are retained in them before being flushed out to adjacent open waters, and their shallow depths both decrease their ability to dilute nutrient (and pollutant) inputs and increase the secondary impacts of nutrients recycled from the sediments. Degradation of coastal waters and development are tied together through inputs of pollutants in runoff, rainfall and groundwater flows. Excess nutrients, especially nitrogen, promote phytoplankton blooms, with adverse consequences including low oxygen, shading of submerged aquatic vegetation, and aesthetic problems.

V.1.1 System Physical Setting

Sesachacha Pond is set along the eastern shoreline of Nantucket Island. The layout of the Sesachacha Pond system is shown in the topographic map detail of Figure V-1. The pond has a surface area of approximately 280 acres. The pond is fully enclosed, but is periodically opened by means of a trench dug across the beach to drain the pond into the Atlantic Ocean.

Similar systems, sometimes referred to as "blind", "intermittently open", or "seasonally open" estuaries, are also found in Australia, on the west coast of the United States, South America and India (Stretch and Parkinson, 2006). Perched estuaries are those that have water levels consistently above mean sea level (MSL) and tend to occur on coastlines that have an energetic wave climate with steep beaches and coarse sediments. It is common practice to artificially breach closed ponds/estuaries when water levels become high, typically to prevent flooding of upland properties and to flush the systems from a build-up of contaminants adversely impacting water quality. The ponds along the south coast of Martha's Vineyard are local examples of where periodic breaching is a regular facet of pond management.

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Figure V-1.   Topographic map detail of Sesachacha Pond, Nantucket Island, Massachusetts.

V.1.2 System Hydrodynamic Setting

In Sesachacha Pond, the hydrodynamic regime is dominated by freshwater inputs to the system from groundwater recharge, surface flow run-off from the watershed, and direct precipitation to the pond's surface. The volume of water in the pond is governed by the balance between additions from freshwater inflow and losses due to evaporation and flow through the eastern beach face into the ocean. On average, the inputs are greater than the losses and the pond elevation gradually rises.

When the pond level is deemed high enough, a trench is cut across the eastern beach. Because the pond level is higher than the ocean, the pond drains. The initial outflow from the pond causes a small channel to be scoured through the beach and the water level in the pond drops. The ephemeral channel across the beach is a balance between the scouring effect of water flowing through it and the filling effect of sediment transport along the beach. Because Sesachacha Pond is relatively small, the initial flush of water scours a very modest channel, while the wave climate on the eastern coast of Nantucket is one of the most energetic in Massachusetts. As a result, the breach channel typically closes very quickly, sometimes before a rising tide can even cause inflow from the ocean into the pond. The result is that these short or failed breaches only remove the top layer of water from the pond. There is very little inflow of water from the ocean and little mixing of the nutrient rich water from the pond with low nutrient

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inflow. As a result, openings that do not allow influx of ocean waters simply lower the water levels and do little to improve the water quality inside the pond. Based on recent information from the Nantucket Marine Department, successful pond breaches remain open for 6 days or more, allowing salinity levels in the pond to approach those of the adjacent Atlantic Ocean waters.

V.2 GEOMORPHIC AND ANTHROPOGENIC EFFECTS TO THE SYSTEM

V.2.1 Pond Management Practices

The barrier beach separating Sesachacha Pond from the Atlantic Ocean was historically breached once or twice per year between the 1930s and 1981 (Aubrey Consulting, Inc., 1989). These man-made openings typically shoaled within two weeks of the breach creation. The reason for breach creation at Sesachacha Pond were to enhance shellfish populations, allow passage of anadromous fish, lower the water level to reduce flooding potential, and control insect populations. Primarily, Sesachacha was managed for shellfish, specifically oysters. According to Town records, prior to 1968 oysters were plentiful in Sesachacha Pond. For example, in 1945, 370 bushels of seed oysters and 500 bushels of adult oysters were removed from Sesachacha Pond and replanted in Madaket and Polpis Harbors. An additional 120 bushels of adult oysters were replanted in Hither Creek. Although Town Reports have not mentioned oyster populations in Sesachacha Pond since 1968, anecdotal information suggests that 300-400 bushels were harvested each year in the early 1970s (Kelly, 1988). In addition, the average density of oysters near Quidnet varied from 59/m^2 in 1981 to 20-25/ m^2 in 1984.

According to long-term salinity records, the pond was not breached between 1981 and 1989, causing a significant reduction in the long-term pond salinity, as shown in Figure V-2. Prior to the early 1980s, the salinity record shows the characteristic fluctuations associated with periodic breaching of the barrier beach. By 1988, the salinity level within the pond had dropped to approximately 2 ppt. In 1989, biological analysis indicated that few if any live oysters remained in the pond.
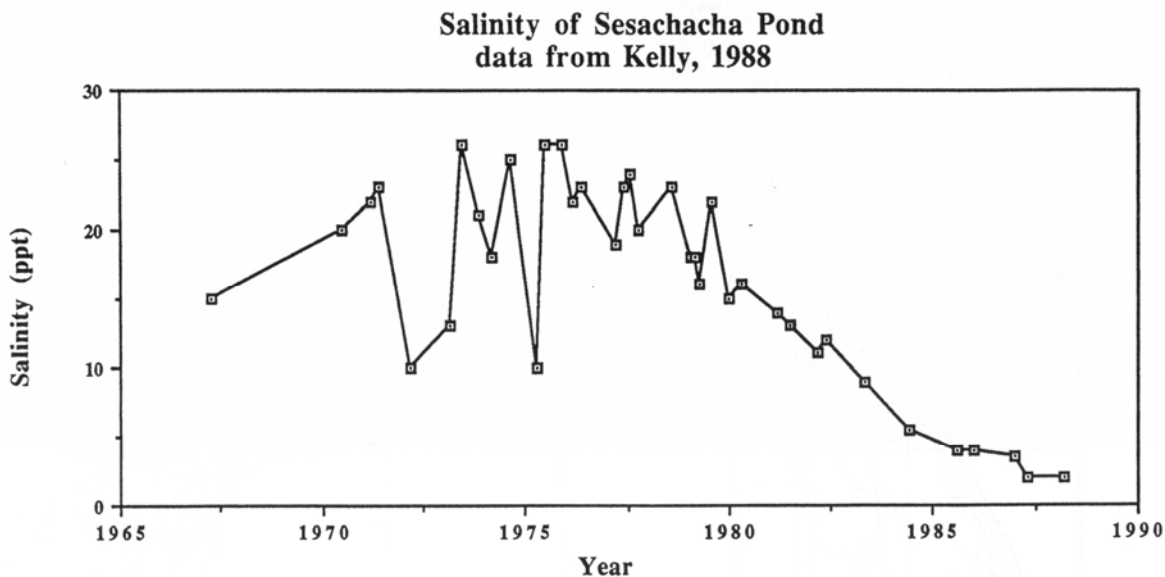
Figure V-2.	Salinity of Sesachacha Pond between 1967 and 1988 (from Kelly, 1988).

Following purchase of the barrier beach property in the late 1980s, the landowner secured environmental permits to breach the barrier periodically. Based on Town records, both spring and fall breaches were attempted between 1997 and 2004 (Figure V-3). The average opening lasted more than 10 days; however, some openings were unsuccessful (i.e. the pond drained, but no ocean water entered the pond) and 'typical' opening existed for 5 to 7 days. As a result of the twice annual barrier beach breaching, salinity levels have increased to pre-1980 levels. Between 1997 and 2004, average annual salinity levels in Sesachacha Pond exceeded 20 ppt for 5 of 8 years.
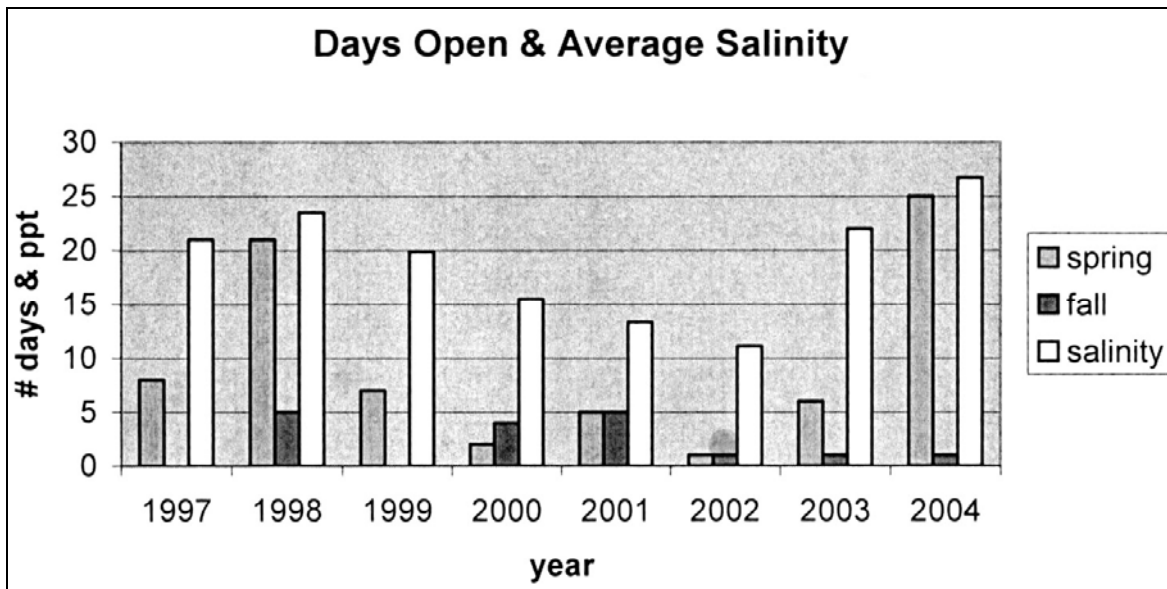
Figure V-3.　　Record of pond openings between 1997 and 2004 indicating the relative success of the opening (in days), as well average annual salinity levels (Curley, 2004).

V.2.2 Shoreline Change Analysis

Shoreline change maps can effectively be used to evaluate the effects of long-term coastal processes. In addition, shoreline change maps also can indicate the effects of short-term changes that often occur as the result of anthropogenic (e.g. development of extensive shore protection structures) or natural (e.g. inlet migration) processes. Prior to developing conclusions and/or management recommendations that depend on shoreline change estimates, it is critical to understand potential errors and uncertainties associated with this type of analysis. Understanding the limitations of shoreline change data is critical for developing appropriate management strategies for shorelines and inlets in areas with relatively low shoreline migration rates, such as Nantucket's east coast.

Shoreline change was evaluated for this study during the time period from 1955 to 2003. The 1955 shoreline was digitized from the National Ocean Service (NOS) T-Sheets. The shorelines depicted on the T-sheets were created by interpreting the high-water shoreline position from controlled aerial photography. The 2003 shoreline was developed by compiling high-water shoreline position from April 2003 color orthophotographs available from MassGIS. The high-water shoreline visible on the orthophotos was digitized by hand using a line-drawing tool in ArcGIS 9.0. Although the high-water shoreline was well marked in most areas, in some instances it was difficult to discern the high-water line based on coloration and other visible

features alone. For these areas, NOAA's LIDAR survey from September 25, 2000 was used to aid in the determination of shoreline position.

Change calculations were made at 40-meter (131 foot) intervals along the outer coast between Squam Head and Sankaty Head using the Automated Shoreline Analysis Program (ASAP) for ArcGIS 9.0. Shore-normal transects were developed using average shoreline angles determined at each analysis point. All transects used for determining change rates were visually inspected to ensure that each was suitability located and properly oriented.

Shoreline change calculated between 1955 and 2003 showed a clear trend in the region around Sesachacha Pond (Figure V-4). To the north, the shoreline has accreted over the past 48 years, at a rate of +2 feet per year on average. Along Sesachacha Pond's eastern edge and the beach immediately to the north and south, the shoreline is essentially stable. The change rates for this half-mile area adjacent to the pond are less than ±0.7 feet per year. The shoreline to the south of Sesachacha Pond is erosional, and increasingly so heading south. The change rate is essentially zero near the pond and increases towards -5 feet per year less than two miles to the south.

The presence of a low shoreline change rate in the area of the Sesachacha Pond openings does not indicate that sediment transport along the outer beach is small in this region. When considering the change rates on the beaches adjacent to the pond, it becomes clear that the area of the breach location is quite active. It just happens that this area lies in a region of transition between long-term accretion to the north and erosion to the south. The major beach nourishment project planned to protect dwellings south of Sesachacha Pond may alter shoreline change along the barrier beach fronting the pond. This potential influx of littoral sediments will increase barrier beach width temporarily, increasing excavation length for the man-made breach. However, this effect should be relatively short-lived.

V.3 HYDRODYNAMIC FIELD DATA COLLECTION AND ANALYSIS

This study of Sesachacha Pond is unique in that while a model of the hydrodynamics in the pond during a breach event is developed, the system was not instrumented during an actual breach event. As a result, there is no hydrodynamic data (pond elevations or velocities) available to directly calibrate the model. A significant effort went towards the development of a sound modeling approach using available data, which is discussed in detail in Section V.3.2 below. Although tide data was not available for a time period when the temporary inlet was open, the hydrodynamic modeling approach provides appropriate parameters for estimating tidal exchange during typical breach events.

In addition to the hydrodynamic data, the pond geometry is an important variable which was collected. System geometry is defined by the shoreline of the pond as well as the water depths throughout the pond. The three-dimensional surface of the pond must be accurately mapped, since the resulting hydrodynamic behavior is strongly dependent upon features such as channel widths and depths, sills, and volumes of the pond system. Therefore, this study included an effort to collect bathymetric information. While the geometry of Sesachacha Pond is straight forward, the varying water depths are an integral part to the water quality modeling.
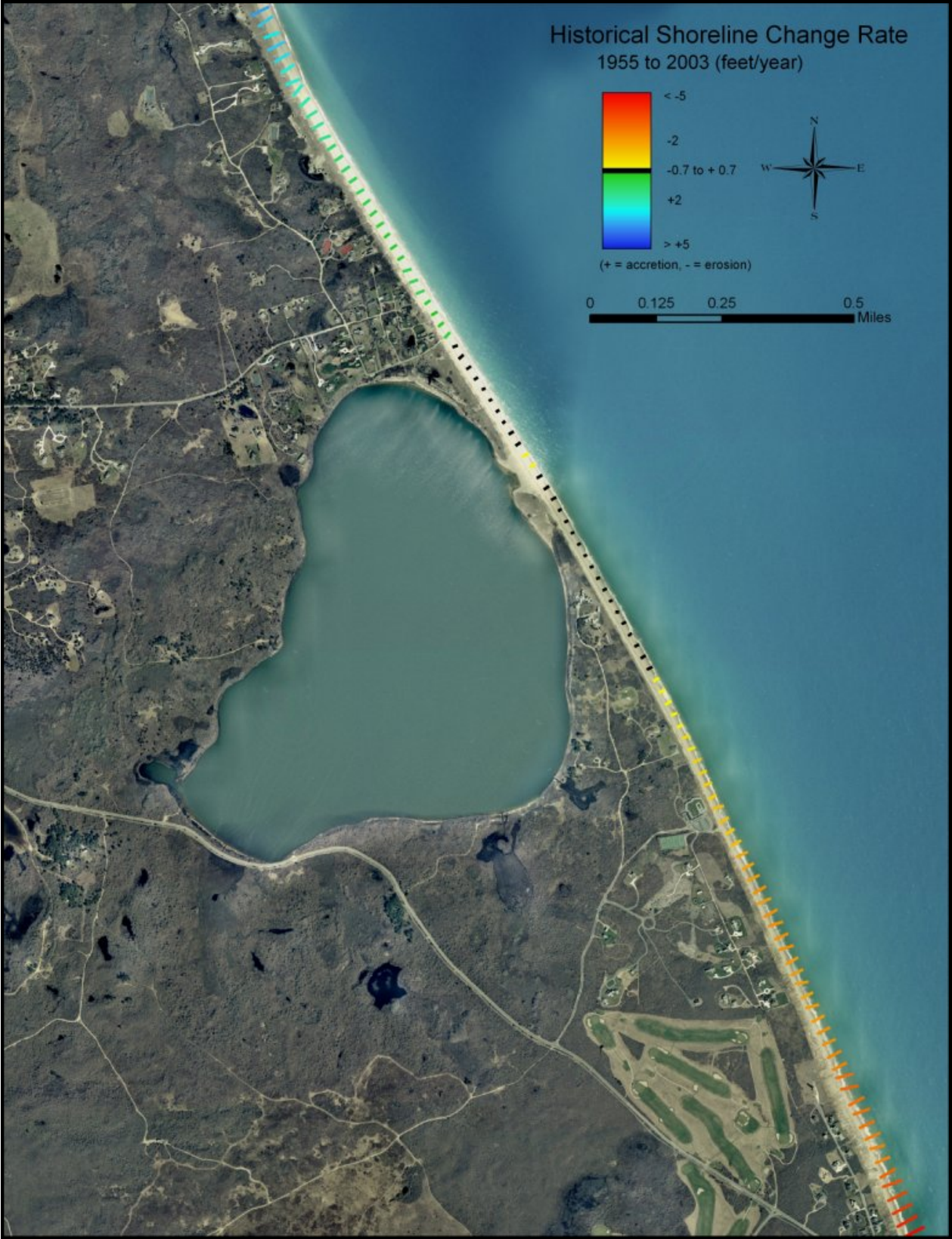
Figure V-4. Historical shoreline change rates (1955-2003) in the area of Sesachacha Pond.

V.3.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Sesachacha Pond system was assembled from a recent boat based hydrographic survey supplemented with data from a previous survey (Aubrey Consulting, 1989). The recent survey was executed specifically as part of the Massachusetts Estuaries Project analysis.

The hydrographic survey of May 25, 2006 was designed to cover the entire main basin of Sesachacha Pond. The survey was conducted from a 14' skiff with an installed precision fathometer (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide horizontal position measurements accurate to approximately 1-3 feet. As the boat was maneuvered around the pond, digital data output from both the echo sounder fathometer and GPS were logged to a laptop computer, which integrated the data to produce a single data set consisting of water depth as a function of geographic position.

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to the Mean Lower Low Water (MLLW) vertical datum. Once rectified, the finished processed data were archived as 'xyz' files containing x-y horizontal position (in Massachusetts State Plan 1983 coordinates) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The tracks followed by the boat during the bathymetry survey are presented in Figure V-5.

V.3.2 Tide Data

The hydrodynamic analysis required for this study of Sesachacha Pond utilizes tide data recorded by the National Oceanic and Atmospheric Administration (NOAA) at Nantucket Harbor. A spring tide event was chosen for the water levels outside the pond. The larger range during a spring tide maximizes the flushing and water exchange if the breach is open over a few tide cycles. A plot of the tide signal used is shown below in Figure V-6. The tidal statistics for the Nantucket Harbor station 1983-2001 Epoch are shown in Table V-1.

Ideally, a station closer to the project site would be used in the absence of field data. However, the only station nearer to Sesachacha Pond is Great Point. A comparison of the tides at Great Point and Nantucket Harbor showed little difference in the tide range and phase between the two stations. Nantucket Harbor was chosen because it is one of NOAA's primary recording stations and hence the tidal statistics are based on recordings made on site, rather than inferred from other stations.

V.4 HYDRODYNAMIC MODEL DEVELOPMENT

The scour of a channel through the beach and the flow of water between the pond and ocean through this channel cannot be directly simulated with the RMA suite of models. Therefore, a computer model independent of RMA-2 was used to simulate the flow through the breach channel. Using this breach model, time varying boundary conditions were developed for RMA-2 model runs of the main basin of Sesachacha Pond, up to the channel.

Figure V-5.   Bathymetry survey lines (yellow) followed by the boat in Sesachacha Pond. The final RMA2 grid used for hydrodynamic and water quality modeling is also shown as the white mesh.

V.4.1 Modeling flow through a breach

When the pond is first opened, the initial trench cut through the beach is scoured out by the rush of water leaving the super-elevated pond. The channel increases in width and depth during this time and over the first few tides cycles if the breach remains open. It would be beyond the scope of this study to model the dynamic growth of the channel during the breach event itself. However, the width and depth of the channel are important variables needed to model the flow between the ocean and Sesachacha Pond. To parameterize variables pertinent to the Sesachacha Pond breach, data from another nearby coastal pond that incorporates similar seasonal management techniques (creation of a breach) was analyzed.

Edgartown Great Pond lies on the southern coast of Martha's Vineyard (Figure V-7) and is the easternmost of the many ponds which line the island's southern coast. Like Sesachacha

Pond, Edgartown Great Pond has no stable tidal inlet and water levels gradually increase over time s groundwater fills the pond. To prevent upland flooding and also to improve water quality, the pond is periodically breached through a channel which is dug through the southern beach. A study of Edgartown Great Pond is planned as a part of the Massachusetts Estuaries Project and a breach event in November, 2004 was monitored. These recordings of pond elevation during the breach event proved invaluable for estimating how a similar breach event in Sesachacha Pond would perform.
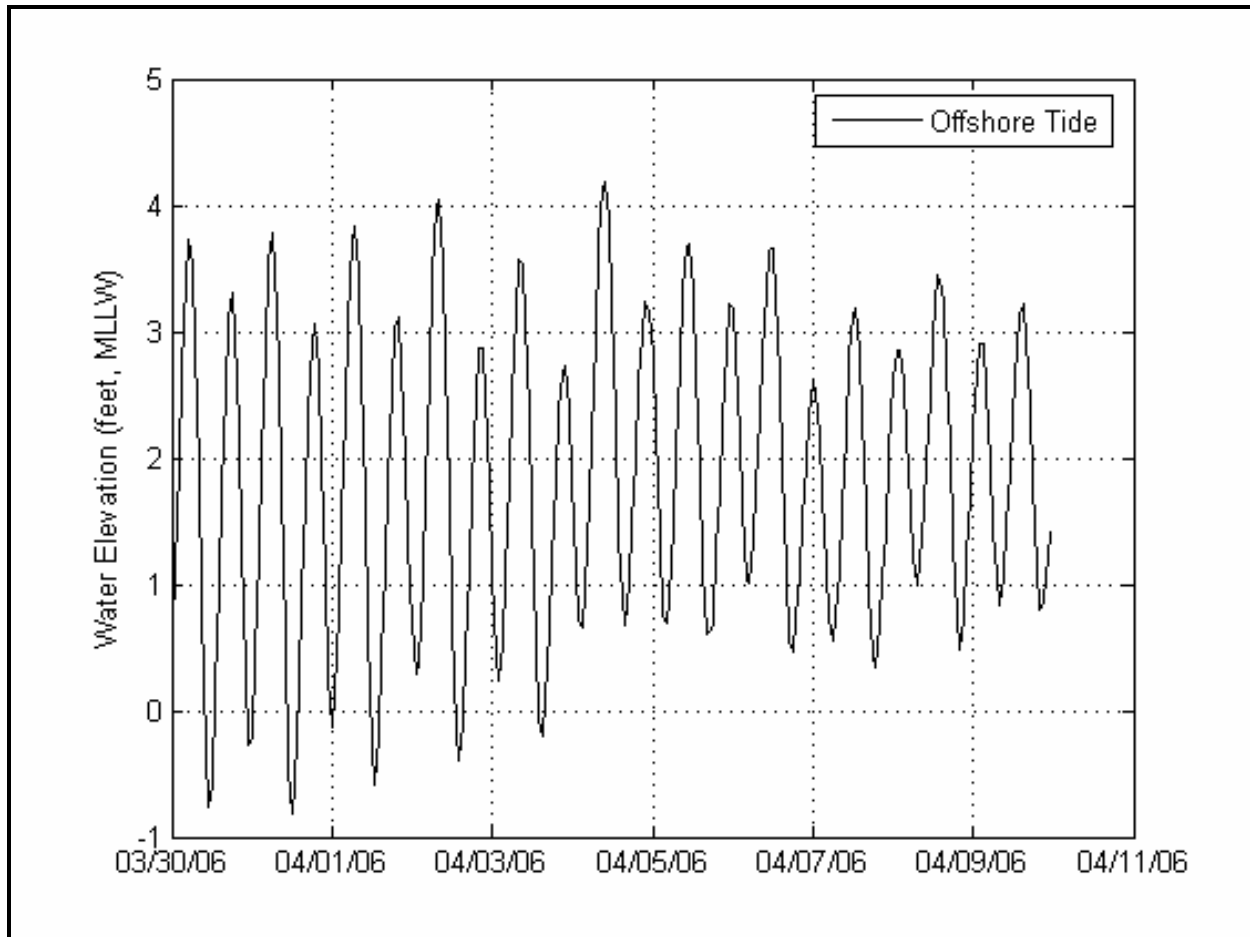
Figure V-6.   Nantucket Harbor tides used for the water level outside Sesachacha Pond for the hydrodynamic model. Elevations are referenced to MLLW.

Table V-1. Tide datums reported by NOAA for Nantucket Harbor. Datum elevations are given relative to MLLW.	
Tide Datum	Elevation (feet)
Highest Recorded (10/30/91)	7.87
MHHW	3.57
MHW	3.24
MTL	1.72
MLW	0.20
MLLW	0.00
Minimum Recorded (2/12/81)	-2.14

Figure V-7.   Area map detail of Edgartown Great Pond, Martha's Vineyard, Massachusetts.

To establish an estimate of the breach channel width, comparisons were made between the Edgartown Great Pond channel and a similar breach in Ellisville Harbor, in Plymouth, MA. A survey of the breach at Edgartown Great Pond showed a channel width of 50-70 feet, while the Ellisville Harbor breach was slightly larger at about 70-80 feet wide. It is likely that the Sesachacha breach would be most similar to that at Edgartown Great Pond, due to a similar wave climate and tide range. A channel width of 60 feet was selected as representative of the breach at both Sesachacha and Edgartown Great Pond.

To estimate the channel scour depth, the flow rate through the channel is needed. Using the data from the Edgartown Great Pond breach event, the water levels following the initial opening could be observed (Figure V-8). This plot shows the elevated water level in the pond at about 3.2 feet MLLW. Around mid-day on November 23, the pond level drops steeply, indicating that the breach had been opened at this time. The pond continued to drain until the tide offshore was higher than the pond elevation. At this time ocean water flowed into the pond. When the tide lowered again, the pond drained until the next rising tide. This continued until approximately December 2, at which time the channel had almost closed and the pond level changes at a much slower rate. Around December 4 tide data indicates that the breach had been completely filled in with sand and there was no longer exchange between the pond and

the ocean. At the very end of the data set, around December 8, the very high tide level reopened the breach at least partially and a small amount of exchange occurred.
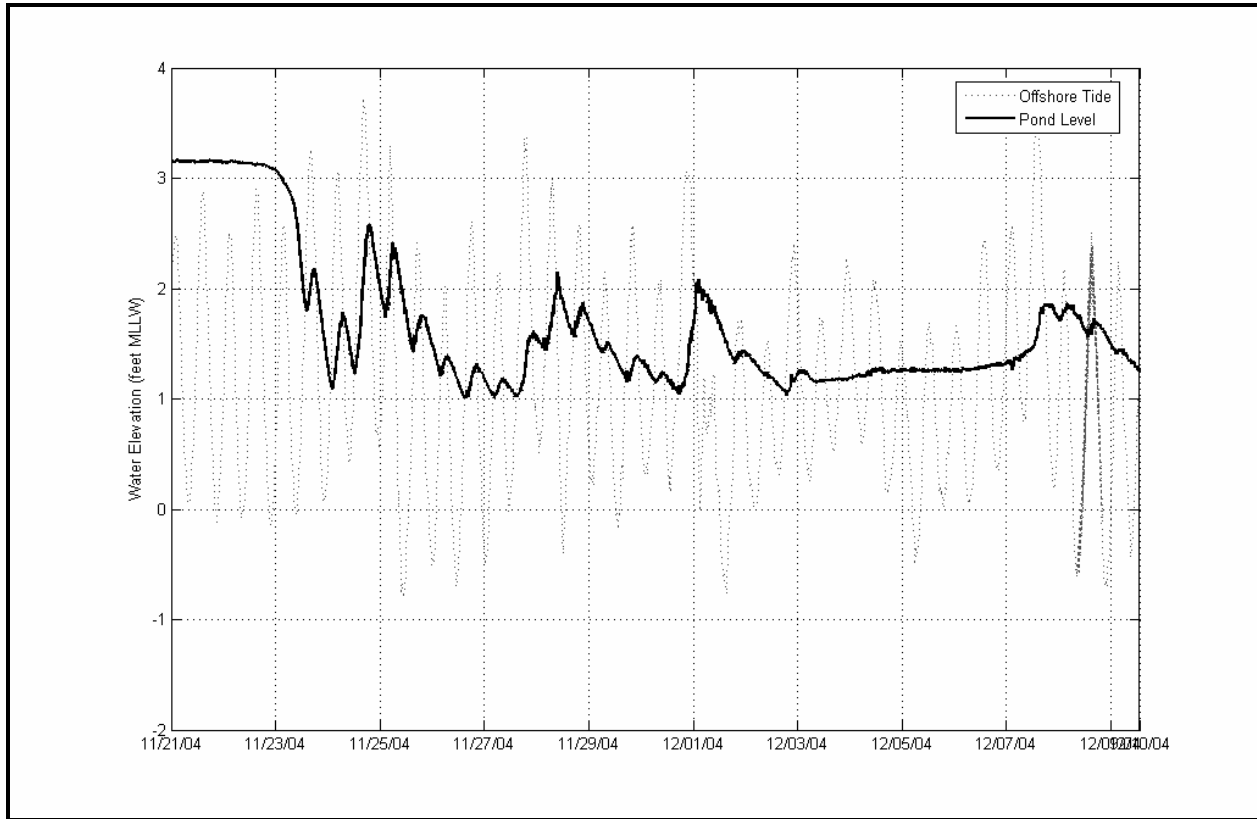
Figure V-8.　　　Water elevations during the breach event in Edgartown Great Pond.

Using these data, an average flow rate out of the pond was measured. The first four times that the pond level was falling after the initial opening were examined to determine the drop in pond elevation and the time over which this drop occurred. Together with the surface area of the pond (approximately 860 acres), these values led to a calculation of 1200 ft³/s of water leaving the pond on average.

With the flow rate and channel width established, the channel depth was calculated using an approach described by the U.S. Army Corps of Engineers (USACE) for the analysis of scour depth at tidal inlets (Hughes, 1999). This equation predicts the depth of the channel, given the flow rate, sediment type and channel width as

$$h = \frac{0.234 q^{8/9}}{[g(S-1)]^{4/9} d^{1/3}}$$

where h is the elevation of the channel bottom relative to the high water level, q is the flow rate divided by the channel width, S is the specific gravity of the sand and d is the average diameter of the sand. A quartz sand (S = 2.65) of diameter 0.5mm was used to represent the sand in this case.

With the initial pond elevation, offshore tides, channel width, and channel depth established, the final step was to estimate the flow in and out of Edgartown Great Pond during the breach event. To compute this volume exchange, the equation of flow over a broad-crested weir was employed. This equation relates the flow rate through the channel to the channel width and height of water above the channel bottom as

$$Q = 3.0bH^{3/2}$$

where Q is the predicted flow rate, b is the channel width and H is the difference in elevation between the high water and the channel bottom.

Using the starting pond level of 3.2 feet MLLW and the recorded offshore tides, a computer model was created to calculate the time-varying flow through the channel. The pond level and offshore tide every 10 minutes was input into the model and the flow rate was calculated. Multiplying the flow rate by the time step yields the total volume of water moving through the channel. If the pond level is higher than the offshore tide, this water is leaving the pond, while a higher water level in the ocean means that water is entering the pond. Knowing the surface area of the pond, the change in pond surface elevation was calculated at each time step. The comparison between the field data and the broad-crested weir model is shown in Figure V-9 below.
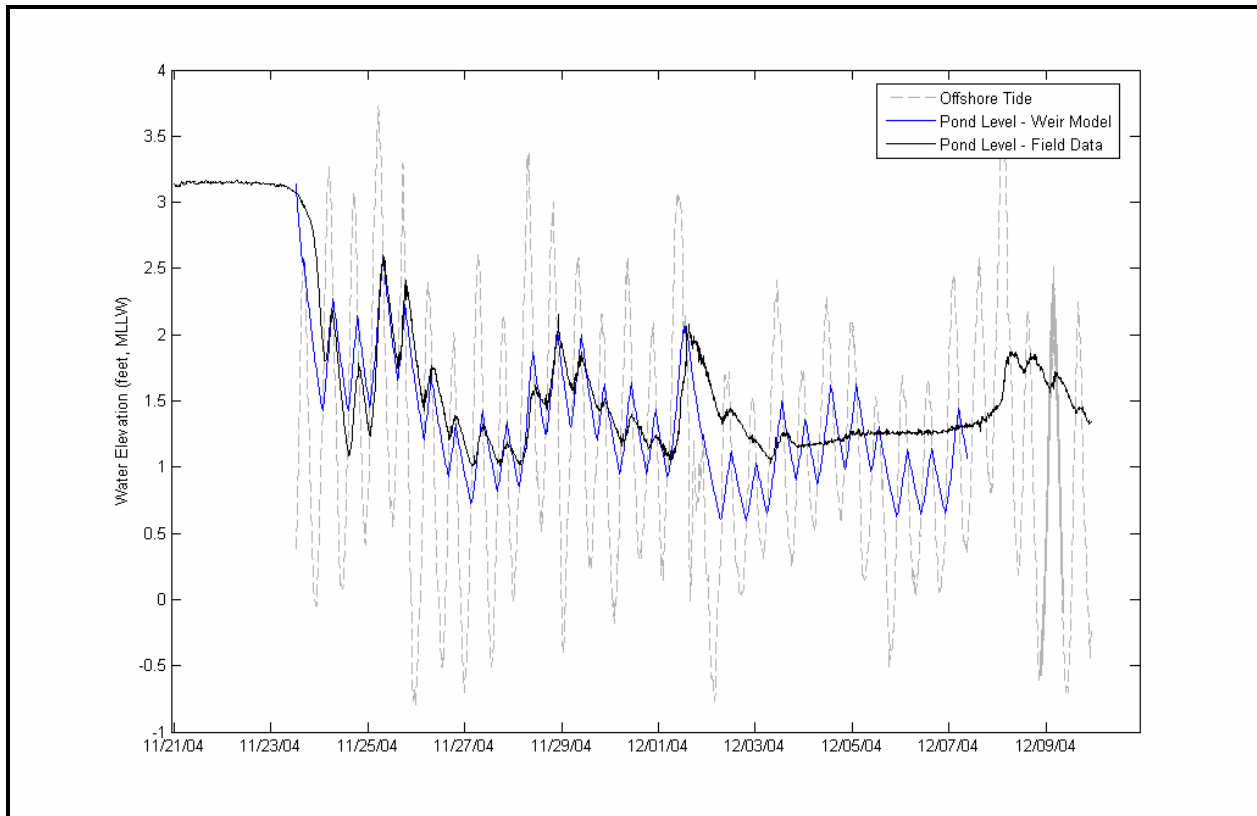
Figure V-9.   A comparison of the broad-crested weir model results with the recorded pond elevations during the breach event at Edgartown Great Pond.

This simple modeling approach yielded excellent agreement with the field data. During the first 5 days (11/23-11/28) the slopes of the weir model prediction and the field data are similar, suggesting that the channel was conveying water in and out of the pond freely.   The following 4 days (11/29-12/2) show the field data having a slightly shallower slope than the model as well as a smaller tide range inside the pond. This indicates that the water was not traveling through the channel freely, suggesting that the opening was beginning to shoal. This is a good reminder that the weir model assumes a fully open channel and makes no approximations for the natural shoaling and eventual closure of the breach. With that caveat in mind, these results provided confidence that the broad-crested weir modeling approach would yield a good approximation of flow during a breach event in Sesachacha Pond (Figure V-10).

V.4.2 Modeling the breach at Sesachacha Pond

The approach described above was employed to estimate the flow through a breach at Sesachacha Pond. The channel scour depth was recalculated for Sesachacha pond using an estimated flow rate. It was assumed that the flow rates in Sesachacha and Edgartown Great Ponds would vary as the ratio of their surface areas. Therefore, in equation form, the breach flowrate associated with Sesachacha Pond can be computed as

$$Q_S = Q_E \frac{A_S}{A_E}$$

where Q and A represent the flow rate and surface area respectively and the subscripts S and E denote Sesachacha and Edgartown Great Ponds respectively. With the surface area of Sesachacha calculated to be approximately 280 acres, the flow rate through the Sesachacha breach was estimated as 391 ft^3/s.

This flow rate and a channel width of 60 feet was used in the USACE scour equation to estimate a scour depth of 1.8 feet below the high water elevation. An initial pond elevation of +5 feet MLLW was used for this analysis. This starting elevation together with the offshore tide and channel geometry was used to predict the surface elevation of the pond during a breach event. The resulting pond elevations were used as the boundary condition for the RMA2 model. A plot of this boundary condition file along with the offshore tide is shown in V-7 below.

V.4.3 RMA2 model theory

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report primarily were generated within the SMS modeling package.

RMA-2 is a finite element model designed for simulating one- and two-dimensional depth-averaged hydrodynamic systems. The dependent variables are velocity and water depth, and the equations solved are the depth-averaged Navier Stokes equations. Reynolds assumptions are incorporated as an eddy viscosity effect to represent turbulent energy losses. Other terms in the governing equations permit friction losses (approximated either by a Chezy or Manning formulation), Coriolis effects, and surface wind stresses. All the coefficients associated with these terms may vary from element to element. The model utilizes quadrilaterals and triangles to represent the system. Element boundaries may either be curved or straight.

The time dependence of the governing equations is incorporated within the solution technique needed to solve the set of simultaneous equations. This technique is implicit; therefore it is unconditionally stable. Once the equations are solved, corrections to the initial estimate of velocity and water elevation are employed, and the equations are re-solved until the convergence criteria is met.
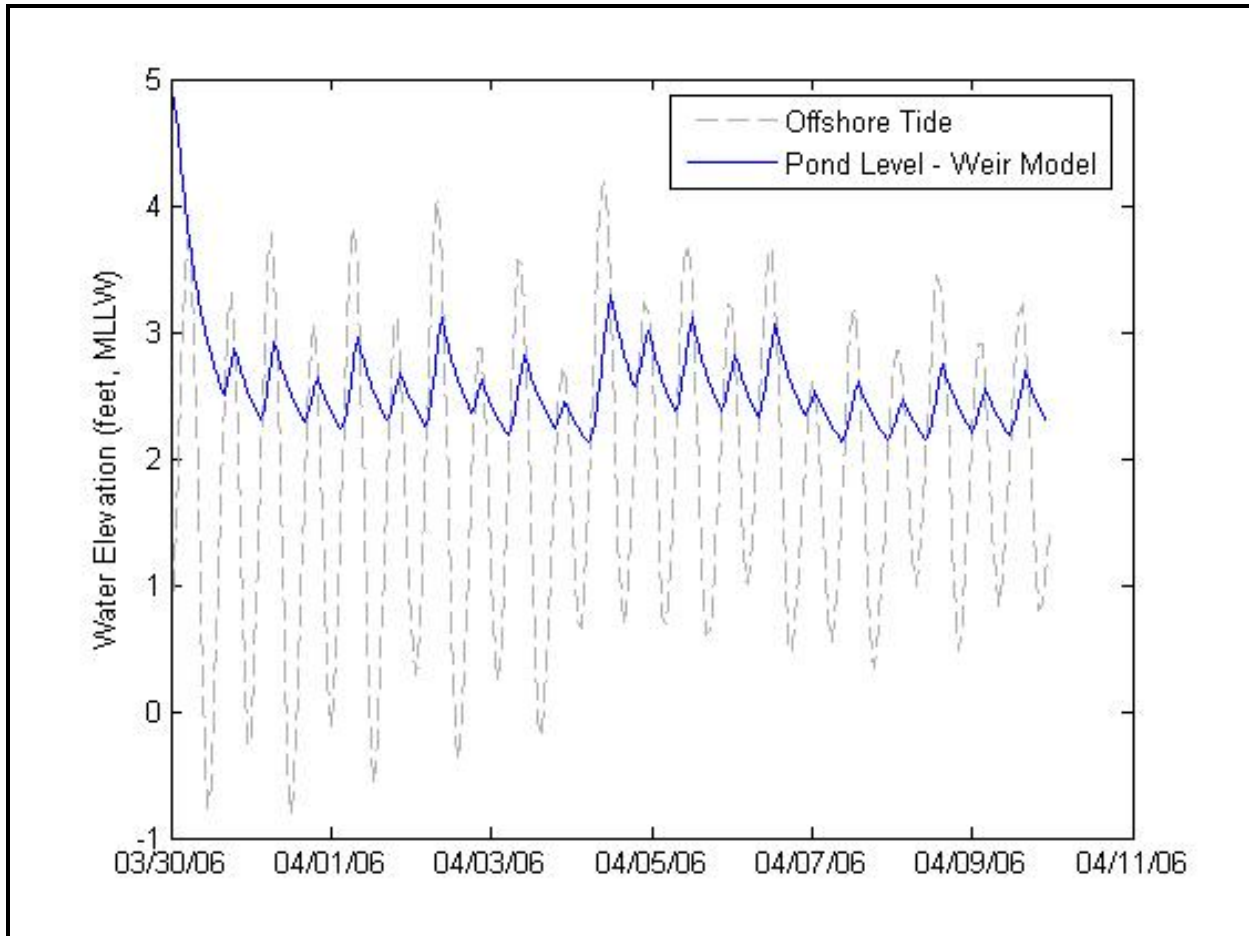
Figure V-10. Weir model results for a breach event at Sesachacha Pond. The blue line represents the predicted water elevation in the pond. These values were used as the boundary condition for the RMA2 hydrodynamic model of the pond.

The time dependence of the governing equations is incorporated within the solution technique needed to solve the set of simultaneous equations. This technique is implicit; therefore it is unconditionally stable. Once the equations are solved, corrections to the initial estimate of velocity and water elevation are employed, and the equations are re-solved until the convergence criteria is met.

V.4.4 RMA2 model development

A two-dimensional hydrodynamic model of Sesachacha Pond was developed using inputs of bathymetry and modeled water surface elevations determined using the broad-crested weir model (Figure V-10). This hydrodynamic model in turn is used as input into the final two-dimensional water quality of the pond.

The finite element mesh created for the pond is shown in Figure V-5, and the final grid with interpolated bathymetry is shown in Figure V-11. The grid is composed of 164 quadratic finite elements (both triangular and quadrilateral elements) and 483 computational nodes. The grid has a maximum depth of -16.5 ft MLLW, which is located in the deep area in the northeastern region of the pond. The bathymetry in the area around the breach in the northeast edge of the pond was edited to be deeper than actually occurs there. This small change was made to ensure model stability and has little impact on the modeled pond elevations and subsequent water quality analysis.
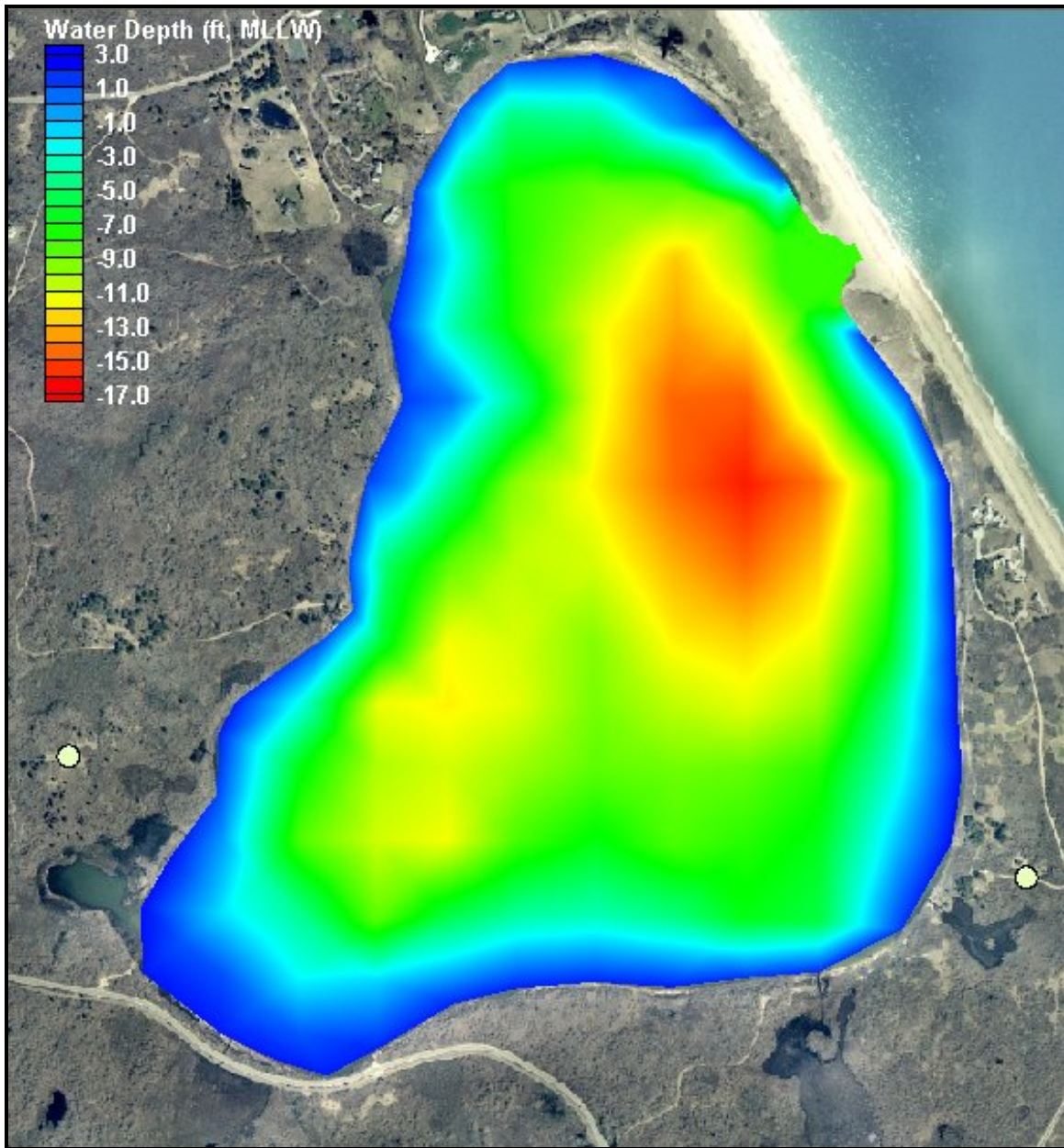
Figure V-11.   Interpolated bathymetric contours of the final RMA2 computational mesh of Sesachacha Pond. Depth contours are relative to the MLLW.

V.5. FLUSHING CHARACTERISTICS

During a sustained breach event, the freshwater inflow would be negligible in comparison to the tidal exchange through the temporary inlet. A rising tide in the Atlantic Ocean creates a slope in water surface from the ocean into the pond. Consequently, water flows into (floods) the pond. Similarly, the pond drains on an ebbing tide. This exchange of water between the pond and ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of the system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

Flushing rate, or residence time, is defined as the average time required for a parcel of water to migrate out of an pond from points within the system. For this study, a **system residence time** was computed as the average time required for a water parcel to migrate from a point within the pond to the entrance of the channel. System residence times are computed as follows:

$$T_{system} = \frac{V_{system}}{P} t_{cycle}$$

where T_{system} denotes the residence time for the system, V_{system} represents volume of the pond at mean tide level, P equals the tidal prism (or volume entering the pond through a single tidal cycle), and t_{cycle} the period of the tidal cycle, typically 12.42 hours (or 0.52 days).

Residence times are provided as a first order evaluation of estuarine water quality. Lower residence times generally correspond to higher water quality; however, residence times may be misleading depending upon pollutant/nutrient loading rates and the overall quality of the receiving waters. As a qualitative guide, system residence times are applicable for systems where the water quality within the entire estuary is degraded and higher quality waters provide the only means of reducing the high nutrient levels. This is a valid approach in this case, since it assumes the ocean has higher quality water relative to the pond.

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the system faster than the tidal circulation can flush the system. Neither are low residence times an indicator of high water quality if the water flushed into the pond is of poor quality. Advanced understanding of water quality will be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The water quality model will provide a valuable tool to evaluate the complex mechanisms governing water quality in the Sesachacha Pond system.

The average volume calculated for Sesachacha pond was 113,497,000 ft[3] with a tidal prism of 5,858,000 ft[3]. This results in a residence time of 10.0 days. This relatively long residence time is not surprising given the small tidal exchange from the temporary channel and the relatively large volume of the pond itself. A detailed discussion of the water quality analysis and results is found in Section VI.

VI. WATER QUALITY MODELING

The water quality modeling analysis approach that has been typically used for other systems that have been studied as part of the Massachusetts Estuaries Project was slightly modified for Sesachacha Pond.

This system differs from all other systems modeled up to this point in time mainly because it does not have inlet that is open at all times to the ocean. Water quality in the Pond is managed presently by opening an inlet bi-annually, once in the spring and once in autumn. The period of time that the inlet remains open after it is breached varies between 1 and 25 days, based on reports of openings made from 1997 through 2004 (Curley, 2004). On average, the pond is open 12 days total a year, which means it is closed off from the ocean more than 96% of the time.

Because Sesachacha Pond is actively managed in such a fashion, the water quality analysis has to include methods for determining conditions in the Pond at times when it is both open and closed to tidal exchange with the ocean. During times when the Pond inlet is breached, the RMA-4 model was used to model water quality constituent dispersion throughout the Pond basin. During the long periods when the breach is closed, a simple mass balance model was developed. As used together in this analysis, these two modeling techniques accurately simulate conditions in the Pond throughout the critical summer months, and provide a method of investigating alternatives to manage pond health.

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort for the Sesachacha Pond system. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of salinity and nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Field measurements and hydrodynamic modeling of the embayment provide essential preparatory input to the water quality model development effort. The pond breach simulation discussed in Chapter V is an important tool for determining the water quality dynamics that are in effect presently, and also for investigating how possibly the pond could be managed differently in the future to further improve water quality conditions. Files of node locations and node connectivity for the RMA-2V model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. For each of the modeling scenarios presented in this chapter, the breach model was run for an extended 30-day period, based on the tide data record from Nantucket Harbor, beginning on March 29, 2005. These tide data were input into the analytical breach model to develop the boundary condition used to force the RMA-2 model of Sesachacha Pond. The hydrodynamics of the breach model are not strongly dependent upon the small inter-monthly variations of the astronomical tide; therefore, the selected 30-day period is considered representative of typical tidal conditions year-round.

VI.1.2 Nitrogen Loading to the Embayments

Three primary nitrogen loads to sub-embayments are recognized in this modeling study: external loads from the watersheds, nitrogen load from direct rainfall on the embayment surface, and internal loads from the sediments. Additionally, there is a fourth load to Sesachacha Pond,

consisting of the background concentrations of total nitrogen (TN) in the waters entering from the Atlantic Ocean during the brief periods when the inlet is open. This load is represented as a constant concentration along the seaward boundary of the RMA-4 model grid during the pond breach simulation period.

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates salinity and total nitrogen concentrations in Sesachacha Pond in response to the existing flushing conditions and loadings, it was necessary to calibrate the model to actual measurements. The refined and approved data for the monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. The multi-year averages present the "best" comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. For Sesachacha Pond, 11 years of salinity data are available between 1992 and 2005, and six years of TN measurements are available between 2000 and 2005.

Table VI-1.	Measured nitrogen concentrations and salinities for the Sesachacha Pond estuarine. "Data mean" values are calculated as the average of the separate yearly means. Data represented in this table were collected in 1992 through 2005 in Sesachacha Pond and the summer of 2005 in the Atlantic Ocean (offshore Pleasant Bay Inlet).					
	total nitrogen			salinity		
Sampling Station Location	data mean (mg/L)	s.d. all data (mg/L)	N	data mean (ppt)	s.d. all data (ppt)	N
Sesachacha Pond	1.197	0.078	48	19.0	6.1	322
Atlantic Ocean	0.232	0.044	17	32.3	0.6	5

VI.2 MODEL DESCRIPTION AND APPLICATION

The overall approach used in the analysis of Sesachacha Pond involves first developing a salinity model of the Pond. Salinity is a conservative water quality constituent, meaning that is has no active sources or sinks other than tidal exchange with the ocean. Because salinity data are conservative, they are excellent calibration data for systems such as Sesachacha. In such simple systems it is an easy task to compute water recharge and rainfall rates based on the observed salinity record.

The Sesachacha Pond analysis requires that both periods when the inlet is open and closed be considered, so a two-part approach was developed. The initial period (when the Pond inlet is breached in the spring and there is tidal exchange with the ocean) is modeled using the RMA-4 dispersion model. The following period when the inlet is closed, and the Pond behaves like a simple reservoir, is simulated using a simple mass balance model which considers fresh water inputs and constituent mass flux into the Pond (which is 0 for the salinity simulation) throughout the simulation period.
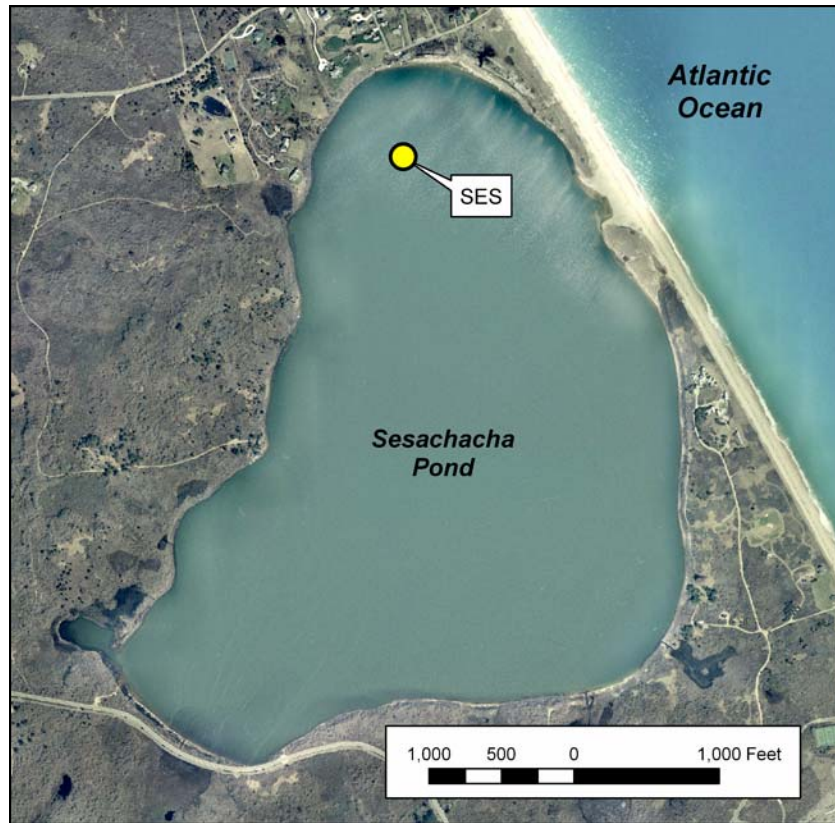
Figure VI-1.   2005 aerial photo showing monitoring station location in Sesachacha Pond that was used in the water quality analysis.

With a calibrated salinity model, a verification of the model is performed using total nitrogen, which is as a non-conservative constituent. For TN, bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. The TN model considers summertime loading conditions, when algal growth is at its maximum. Total nitrogen modeling is based upon various data collection efforts and analyses presented in previous sections of this report. Nitrogen loading information was derived from the Cape Cod Commission watershed loading analysis (using watersheds delineated originally by the USGS and modified by WHOI), as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements were utilized as model boundaries and as calibration data.

VI.2.1 Model Formulation

VI.2.1.1 Dispersion Model

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of water quality constituent dispersion in Sesachacha Pond during the periods when it is open to the ocean. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of the Pond. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod embayments, including systems other Massachusetts estuarine systems such as Pleasant Bay (Howes *et al.*, 2006); Falmouth (Howes *et al.*, 2005); and Mashpee, MA (Howes *et al.*, 2004).

The formulation of the model is for two-dimensional depth-averaged systems in which concentration in the vertical direction is assumed uniform. The depth-averaged assumption is justified since vertical mixing by wind and tidal processes prevent significant stratification in the modeled sub-embayments. The governing equation of the RMA-4 constituent model can be most simply expressed as a form of the transport equation, in two dimensions:

$$\left(\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} \right) = \left(\frac{\partial}{\partial x} D_x \frac{\partial c}{\partial x} + \frac{\partial}{\partial y} D_y \frac{\partial c}{\partial y} + \sigma \right)$$

where c in the water quality constituent concentration; t is time; u and v are the velocities in the x and y directions, respectively; D_o and D_{ee} are the model dispersion coefficients in the x and y directions; and σ is the constituent source/sink term. Since the model utilizes input from the RMA-2 model, a similar implicit solution technique is employed for the RMA-4 model.

The model is therefore used to compute spatially and temporally varying concentrations c of the modeled constituent (i.e., total nitrogen), based on model inputs of 1) water depth and velocity computed using the RMA-2 hydrodynamic model; 2) mass loading input of the modeled constituent; and 3) user selected values of the model dispersion coefficients. Dispersion coefficients used for each system sub-embayment were developed during the calibration process. During the calibration procedure, the dispersion coefficients were incrementally changed until model concentration outputs matched measured data.

The RMA-4 model can be utilized to predict both spatial and temporal variations in total for a given embayment system. At each time step, the model computes constituent concentrations over the entire finite element grid and utilizes a continuity of mass equation to check these results. Similar to the hydrodynamic model, the water quality model evaluates model parameters at every element at 10-minute time intervals throughout the grid system. For this application, the RMA-4 model was used to predict time varying salinity and total nitrogen concentrations throughout Pond through the course of a month-long inlet opening.

VI.2.1.2 Mass Balance Model

During the extended periods when Sesachacha Pond is closed off from the Ocean, the system is modeled as a simple well mixed reservoir. The concentration c is a function of time t, and can be determined using the relationship

$$c(t) = \frac{m_o + t \dfrac{dm}{dt}}{V_o + t \dfrac{dV}{dt}},$$

Where m is the total mass of the modeled constituent, V is the volume of the Pond and the subscript o is used to designate the initial conditions. For the salinity model, the mass flux of salt (dm/dot) into the pond is zero. Using salinity data records from the summers of 1998, 2003, 2004 and 2005, a mass balance analysis of salt was performed to determine the rate of groundwater flow and salt flux through the barrier beach to the Ocean. This flow is the only possible sink for salinity in the Pond system. The four years used for this analysis were selected because in each of these years there was a successful springtime breaching of the pond. These breachings raised salinities in the Pond initially, and over the course of the summer, salinities slowly dropped as the Pond was diluted by ground water recharge and rainfall.

By this analysis, the groundwater flow out of the Pond was determined to be less than 10

percent of the flow in from the Pond's watershed and direct rainfall. The salinity sink through the barrier beach was therefore assumed to be not significant. The net flux of salt is therefore zero, and the net volume flux of water is simply the recharge rate plus direct rainfall minus evaporation. For the TN model, the mass flux of nitrogen is set to the sum of the watershed, atmospheric, and benthic loads.

VI.2.2 Boundary Condition Specification

Mass loading of nitrogen into the model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed and direct atmospheric deposition loads for Head of the Harbor were evenly distributed at grid cells that formed the perimeter of the sub-embayment. Benthic regeneration loads were distributed among another sub-set of grid cells which are in the interior portion of each basin.

The loadings used to model present conditions in Sesachacha Pond are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment, resulting in a total flux for the system (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. The benthic flux presented in Table VI-2 represents the net flux for the entire pond. Sediments in deeper regions (>4.5 meters deep) of the Pond tend to have negative fluxes, which indicates that they are a nitrogen sink. The N production of the bottom sediment in shallower areas is greater than this sink, and as a result, the net flux from the whole pond is positive.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified for the dispersion model. The model uses concentrations at the open boundary during the flooding tide periods of the RMA-4 model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The TN boundary concentration in the Atlantic Ocean region offshore the Pond was set at 0.232 mg/L, based on SMAST data collected offshore Pleasant Bay in the summer of 2005. For the salinity model, the offshore concentration was set at 32.3 ppt.

Table VI-2.	Sub-embayment and surface water loads used for total nitrogen modeling of Sesachacha Pond, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions** for the listed sub-embayments.		
sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Sesachacha Pond	0.973	3.115	20.376

VI.2.3 Development of Present Conditions Model

To develop the water quality model of present conditions for Sesachacha Pond, the RMA-4 dispersion model and the mass balance model were used together to simulate salinities in the Pond during the period from April through November 2004. This time period was chosen because the Spring breach of the Pond lasted 25 days, which is longer than average, which resulted in a wider range of salinities in the Pond that year.

First, the breach was modeled using RMA-4 and the RMA-2 hydrodynamic model results for a simulated 30-day opening. Output from the dispersion model is presented in Figure VI-2. Initially, the Pond salinity is 16.7 ppt. Over 25 days and many tide cycles, the Pond salinity rises to 25.7 ppt. The model output compares exceptionally well with Pond measurements made after the breach closing (25.2 ppt).

For the six month period following the closing of the breach (May through November), the mass balance model was used. This model requires an initial salinity and pond volume, as well as net fresh water flux. The initial salinity (25.7 ppt) was taken from day 25 of the dispersion model run. The initial Pond volume was determined to be 106,700,000 ft^3, based on results from the hydrodynamic model. The net freshwater input to the Pond was determined to be 1.5 ft^3/sec, based on the salt balance analysis performed using the monthly data available from the spring to fall period of 2004. Though a breach was attempted in the fall of 2004, it is apparent from the salinity data record that there was no tidal exchange. The pond elevation would have dropped during the failed breach, and this reduction in volume in the fall was accounted for in the model. The effect on the modeled salinities from this failed breach is small.

The comparison of modeled verses measured salinities between April and November 2004 are presented in Figures VI-3 and VI-4. The comparison shows that the combined dispersion and mass balance models are able to simulate salinities will a high degree of skill, with an R^2 correlation of 0.75 and an rms error of 0.89 ppt. Also in Figure VI-3, the results of a model sensitivity analysis are shown. Model output for two additional cases, where the recharge rates were changed to be 4.1 (from the Cape Cod Commission) and 0 ft^3/sec, shows how the model behaves as the rate is varied. This shows that the model is very sensitive to the applied recharge rate, and further indication that the 1.5 ft^3/sec used to simulate this period in 2004 is close to the actual conditions of the pond during at this time.

Figure VI-2.   RMA-4 salinity dispersion model output for simulation of the spring 2004 opening of Sesachacha Pond. For this opening event, the inlet allowed tidal exchange with the Atlantic Ocean for 25 days before it closed again.

Figure VI-3.   Comparison of measured (black circles) and modeled (red triangles) salinities through the summer of 2004, beginning with the spring breaching of an inlet to the Atlantic Ocean. The first two data points bracket the period of time that the inlet was open, and the Pond was tidally flushed. This breach period was simulated using the RMA-4 model of the Pond. Between May and November, the breach was closed, which prevented any tidal exchange. This period through the summer was simulated using the mass balance model. Results of the sensitivity analysis are also presented, showing model output using recharge rate determined by the Cape Cod Commission (CCC) and zero recharge.

Figure VI-4.   Model salinity target values are plotted against measured concentrations, together with the unity line, for the simulation period from May through November 2004. RMS error for this model verification run is 0.89 ppt and the R^2 correlation coefficient is 0.75.

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VI.2.4 Total Nitrogen Model Verification

With the completion of the salinity model, it was possible to verify the model calibration by modeling total nitrogen, which is a water quality constituent that is completely independent of salinity.

The dispersion model was again run to simulate TN concentrations through the 25-day breach period starting in late April 2004. An open ocean TN concentration of .232 mg/L was used together with the nitrogen mass loading rates presented in Table VI-2 for Sesachacha Pond. As the Pond tidally flushed through the breach, TN concentrations dropped from the initial 1.1 mg/L to 0.29 mg/L at 25 days, as can be seen in Figure VI-5. This result compares very well again to measurements. The observed TN concentration measured soon after the breach closed was 0.28 mg/L, which is only 0.01 mg/L less that the modeled concentration.

Following the dispersion model, the mass balance model was used to simulate the period following the breach closure in May. This model used the same N mass loading rates as the dispersion model and included the same 1.5 ft^3/sec freshwater input used in the modeling of salinity.

Model output is compared to measurements for the entire spring to fall 2004 period in Figure VI-6 and VI-7. Similar to the results of the salinity model of Sesachacha Pond, the comparison demonstrates a high degree of modeling skill, with an R^2 correlation of 0.89 and an rms error of 0.17 mg/L. Model sensitivity to the applied recharge rate is indicated also in Figure VI-6. Rates were varied between the CCC estimate of the rate (4.1 ft^3/sec) and zero. Like the salinity analysis, the results show that the model is very sensitive to the applied recharge rate, and indicate that the 1.5 ft^3/sec used to simulate this period in 2004 is close to actual conditions.
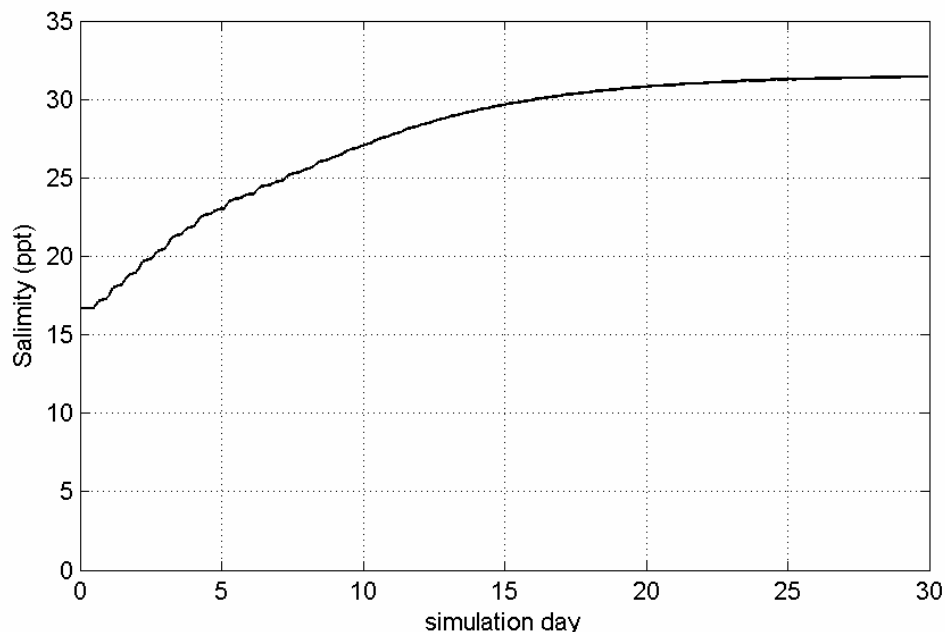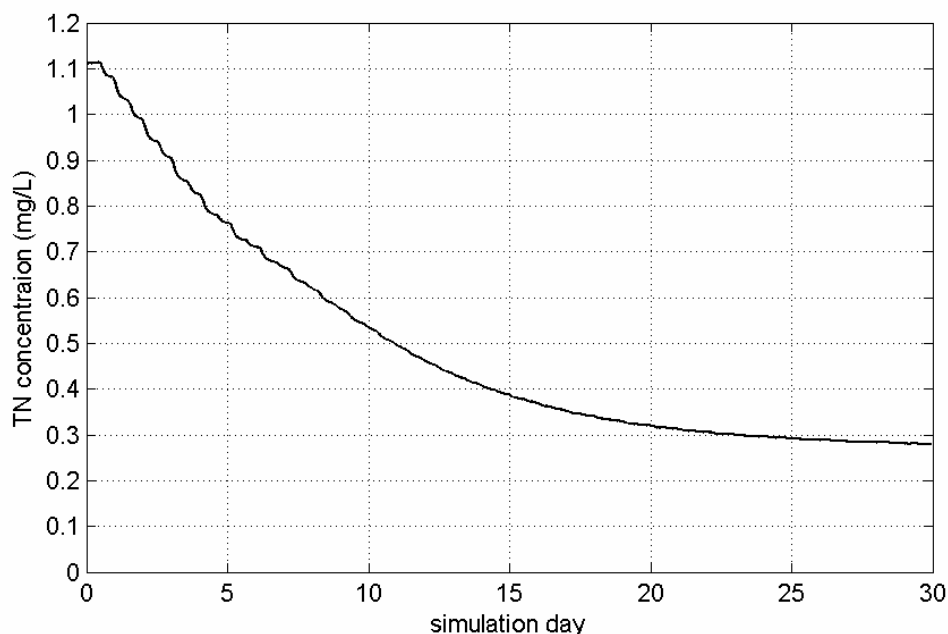

Figure VI-5. RMA-4 total nitrogen dispersion model output for simulation of the spring 2004 opening of Sesachacha Pond. For this opening event, the inlet allowed tidal exchange with the Atlantic Ocean for 25 days before it closed again.
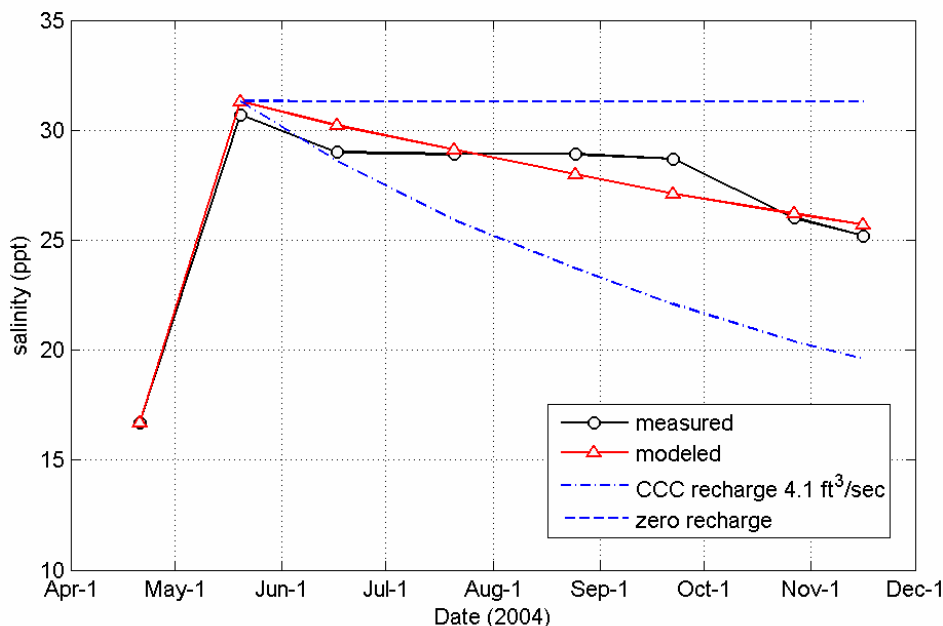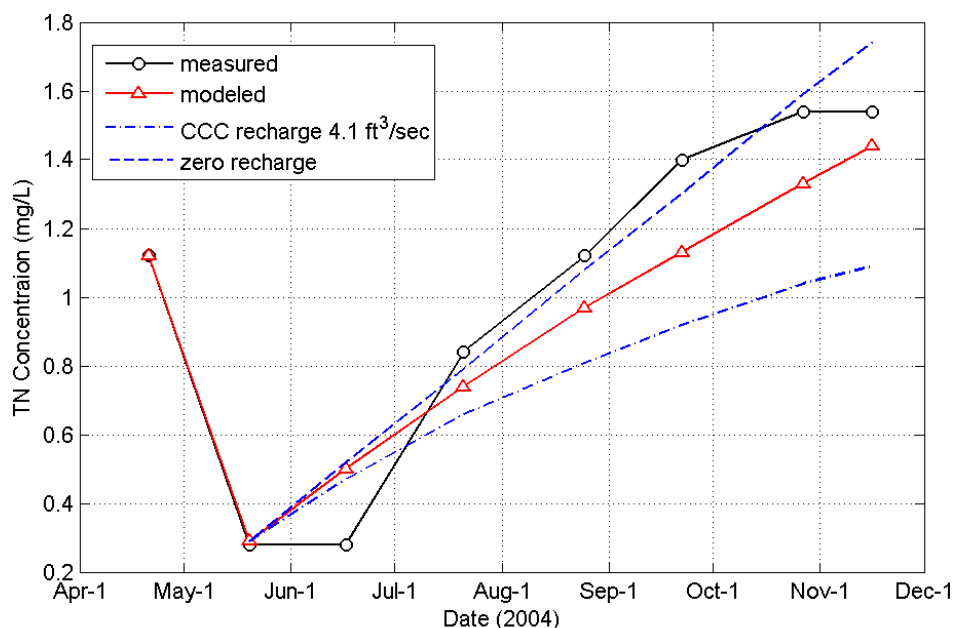
Figure VI-6.   Comparison of measured (black circles) and modeled (red triangles) total nitrogen concentrations through the summer of 2004, beginning with the spring breaching of an inlet to the Atlantic Ocean. The first two data points bracket the period of time that the inlet was open, and the Pond was tidally flushed. Between May and November, the breach was closed, which prevented any tidal exchange. Results of the sensitivity analysis are also presented, showing model output using recharge rate determined by the Cape Cod Commission (CCC) and zero recharge.

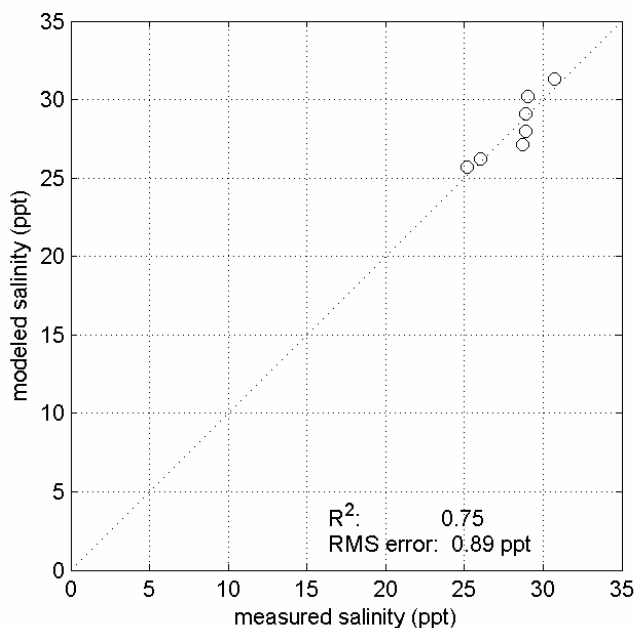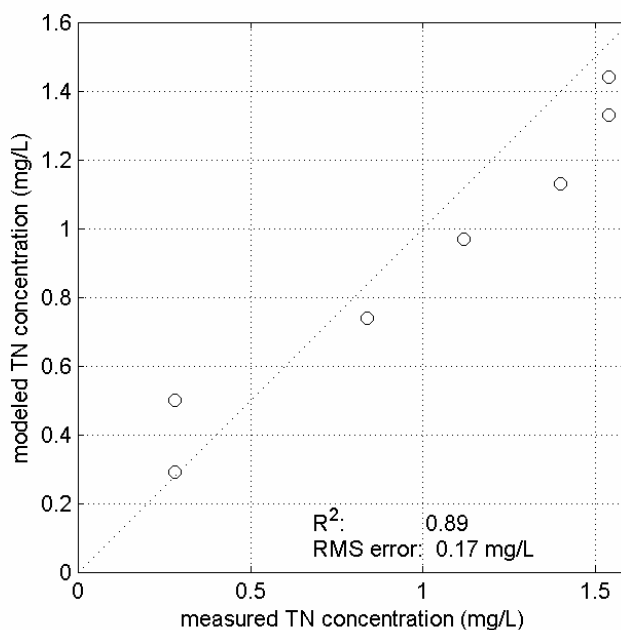Figure VI-7.   Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line, for the simulation period from May through November 2004.. Computed correlation (R^2) and error (rms) for the model are also presented.

Finally, Table VI-3 presents a comparison of modeled TN concentrations and salinities through the complete 30-day period simulated using the breach model hydrodynamics together with the dispersion model. For both modeled constituents, it is shown that concentrations do not change much after 20 days. The half-life of TN during the breach is approximately 9 days, for the modeled conditions.

Table VI-3.	Model TN concentrations and salinities verses inlet days open. For modeled Spring though Fall 2004 conditions.	
duration of opening	TN concentration	Salinity
days	mg/L	ppt
0	1.12	16.7
5	0.76	18.9
10	0.53	22.2
15	0.39	24.3
20	0.32	25.3
25	0.29	25.7
30	0.28	25.8

VI.2.5 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations in Sesachacha Pond, the standard "build-out" and "no-load" water quality modeling scenarios were run. These runs included two "build-out" scenarios, based on potential development (described in more detail in Section IV), and a "no anthropogenic load" or "no load" scenario assuming only atmospheric deposition on the watershed and sub-embayment, as well as a natural forest within each watershed. Comparisons of the alternate watershed loading analyses are shown in Table VI-4. Loads are presented in kilograms per day (kg/day) in this Section, since it is inappropriate to show benthic flux loads in kilograms per year due to seasonal variability.

Table VI-4.	Comparison of sub-embayment watershed loads used for modeling of present, build-out (scenarios "A" and "B"), and no-anthropogenic ("no-load") loading scenarios of Sesachacha Pond. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.				
sub-embayment	present load (kg/day)	build-out (kg/day)	build-out change	no load (kg/day)	no load % change
Sesachacha Pond	0.973	1.104	+11.9%	0.575	-69.2

VI.2.5.1 Build-Out

A breakdown of the total nitrogen load entering the Pond for the modeled Build-out scenario is shown in Table VI-5. The benthic flux for the build-out scenarios is assumed to vary proportional to the watershed load, where an increase in watershed load will result in an increase in benthic flux (i.e., a positive change in the absolute value of the flux), and *vise versa*.

Projected benthic fluxes (for both the build-out and no load scenarios) are based upon projected PON concentrations and watershed loads, determined as:

$$(Projected\ N\ flux) = (Present\ N\ flux) * [PON_{projected}]/[PON_{present}]$$

where the projected PON concentration is calculated by,

$$[PON_{projected}] = R_{load} * \Delta PON + [PON_{(present\ offshore)}],$$

using the watershed load ratio,

$$R_{load} = (Projected\ N\ load) / (Present\ N\ load),$$

and the present PON concentration above background,

$$\Delta PON = [PON_{(present\ flux\ core)}] - [PON_{(present\ offshore)}].$$

Table VI-5.	**Build-out scenario** sub-embayment and surface water loads used for total nitrogen modeling of the Sesachacha Pond system, with total watershed N loads, atmospheric N loads, and benthic flux.		
sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Sesachacha Pond	1.104	3.115	20.967

Following development of the nitrogen loading estimates for the build-out scenarios, the dispersion model was run to determine nitrogen concentrations within in the Pond (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., the Atlantic Ocean) remained identical to the existing conditions modeling scenario.

For the modeled build-out scenario, the increase in modeled TN concentrations is less than 1% through the entire breach simulation. Using the mass balance model to extend the build-out simulation to November 2004, the final concentration is computed to be 1.47 mg/L, or only 0.03 mg/L greater than for present conditions.

VI.2.5.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering the Pond sub for the no anthropogenic load ("no load") scenarios is shown in Table VI-6. The benthic flux input to each embayment was reduced (toward zero) based on the reduction in the watershed load (as discussed in §VI.2.6.1). Compared to the modeled present conditions and build-out scenario, atmospheric deposition directly to each sub-embayment becomes a greater percentage of the total nitrogen load as the watershed load and related benthic flux decrease.

Table VI-6.	"**No anthropogenic loading**" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Sesachacha Pond system, with total watershed N loads, atmospheric N loads, and benthic flux		
sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Sesachacha Pond	0.575	3.115	18.583

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations in the Pond. Again, total

nitrogen concentrations in the receiving waters (i.e., Atlantic Ocean) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was small. Similar to build-out, modeled changes where small. The decrease in modeled TN concentrations is less than 1% through the entire breach simulation. Using the mass balance model to extend the build-out simulation to November 2004, the final concentration is computed to be 1.32 mg/L, or only 0.12 mg/L less than for present conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Sesachacha Pond embayment system in the Town of Nantucket, MA, our assessment is based upon data from the water quality monitoring database developed by the Town of Nantucket Marine Department and our surveys of eelgrass distribution, benthic animal communities and sediment characteristics, and dissolved oxygen records conducted during the summer and fall of 2002. These data form the basis of an assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for this system (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

There are a variety of indicators that can be used in concert with water quality monitoring data for evaluating the ecological health of embayment systems. The best biological indicators are those species which are non-mobile and which persist over relatively long periods, if environmental conditions remain constant. The concept is to use species which integrate environmental conditions over seasonal to annual intervals. The approach is particularly useful in environments where high-frequency variations in structuring parameters (e.g. light, nutrients, dissolved oxygen, etc.) are common, making adequate field sampling difficult.

As a basis for a nitrogen thresholds determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll a (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed a dissolved oxygen sensor within the central portion of the Sesachacha Pond system. In this manner a record of the frequency and duration of low oxygen conditions during the critical summer period was obtained. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Sesachacha Pond System was conducted for comparison to historic records (C. Costello - DEP Eelgrass Mapping Program and MEP Technical Team members from SMAST). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts and the islands, the primary cause appears to be related to increases in embayment nitrogen levels. However, not all embayments or all regions of an embayment are structured to support eelgrass, due to their depth, natural depositional pattern or ecological type (e.g. salt marshes or tidal flats). Within the Sesachacha Pond System, the ability to support eelgrass was assessed as well as potential temporal changes in eelgrass distribution to evaluate increases (nitrogen loading) or decreases (increased flushing-more frequent inlet openings) in nutrient enrichment.

In areas that do not support eelgrass beds, benthic animal indicators were used to assess the level of habitat health from "healthy" (low organic matter loading, high D.O.) to "highly stressed" (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of their habitat. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life-history information on the species and a wide variety of field studies within southeastern Massachusetts waters, including the Wild Harbor oil spill, benthic population studies in Buzzards Bay (Woods Hole Oceanographic Institution) and New Bedford (SMAST), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H') and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 3.8 mg L^{-1}. Massachusetts State Water Quality Classification indicates that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1}. The tidal waters (during barrier beach breach events) of the Sesachacha Pond System are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality. It is through the MEP and TMDL processes that management actions are developed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, an autonomously recording oxygen sensor was moored 30 cm above the embayment bottom within the central region of the Sesachacha Pond System (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. The instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during the 67 day deployment focused on the critical July through mid-September interval. All of the mooring data from the Sesachacha Pond embayment system was collected during the summer of 2002.
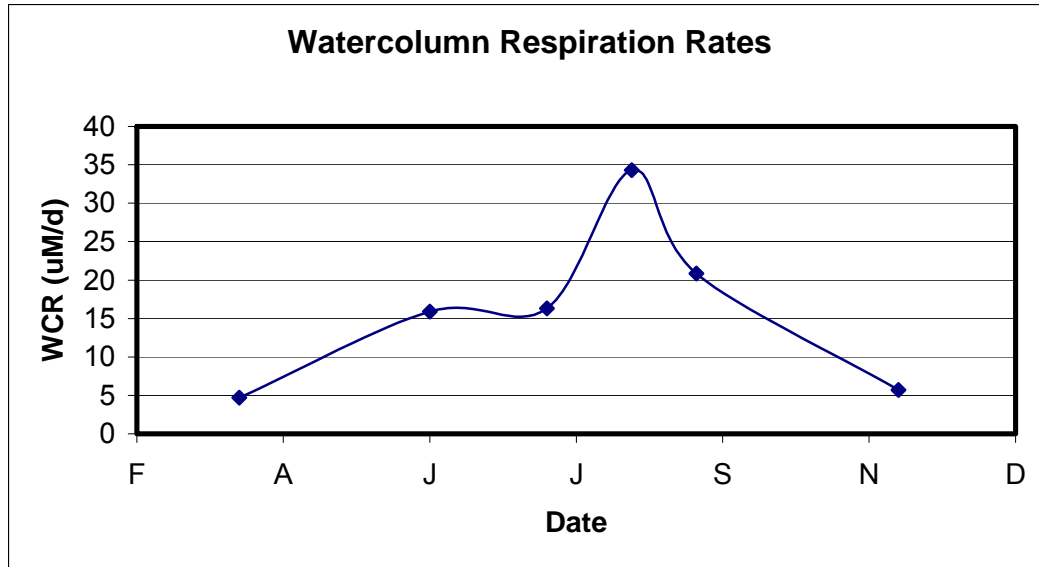
Figure VII-1.   Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Figure VII-2.   Aerial Photograph of the Sesachacha Pond system in Falmouth showing locations of Dissolved Oxygen mooring deployments conducted in the summer of 2002.

Similar to many other embayments in southeastern Massachusetts, Sesachacha Pond, a great salt pond, showed high frequency variation in dissolved oxygen levels, apparently related to diurnal and sometimes tidal influences. The degree of the diurnal variation and observed hypoxia are consistent with a nitrogen enriched, eutrophic, salt pond (Figure VII-3). 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 temporal record of dissolved oxygen also captured a very low oxygen event, where levels declined to below 4 mg L^{-1} for extended periods and below 2 mg L^{-1} on multiple dates. During this low oxygen period in late August-early September, there was an interval of extremely large diurnal variations (~6 mg L^{-1}) that coincided with a very large phytoplankton bloom. Chlorophyll levels at the height of the bloom were in the hypereutrophic range, exceeding 100 ug L^{-1} (Figures VII-3, Figure VII-4). The observed high degree of temporal variation in bottom water dissolved oxygen and chlorophyll concentration underscores the need for continuous monitoring within these types of systems.

Dissolved oxygen and chlorophyll a records were examined both for temporal trends and to determine the percent of the 67 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

The dissolved oxygen records indicate that the Sesachacha Pond system is currently under seasonal oxygen stress, consistent with nitrogen enrichment (Table VII-1). That the cause 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 improved in the system with the onset of autumn, although the system showed oxygen depletions 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. The oxygen data is consistent with high organic matter loads from phytoplankton production, as indicated by the observed chlorophyll a levels. Both the oxygen and chlorohyll records indicate a highly nitrogen enriched system, significantly over its nitrogen threshold, the upper limit which supports healthy habitat quality.
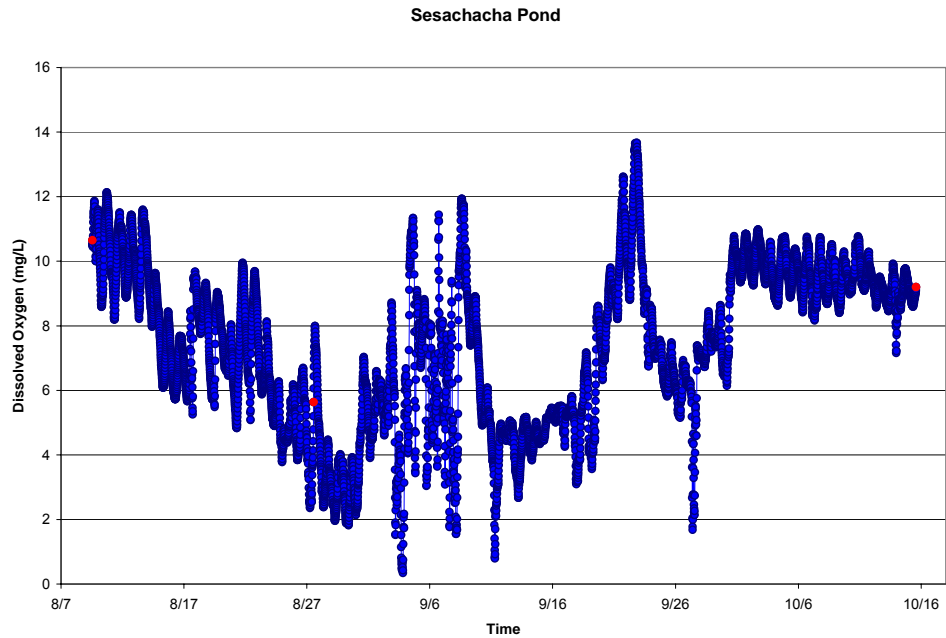
Sesachacha Pond

Figure VII-3.   Bottom water record of dissolved oxygen at the Sesachacha Pond station, summer 2002. Calibration samples represented as red dots.
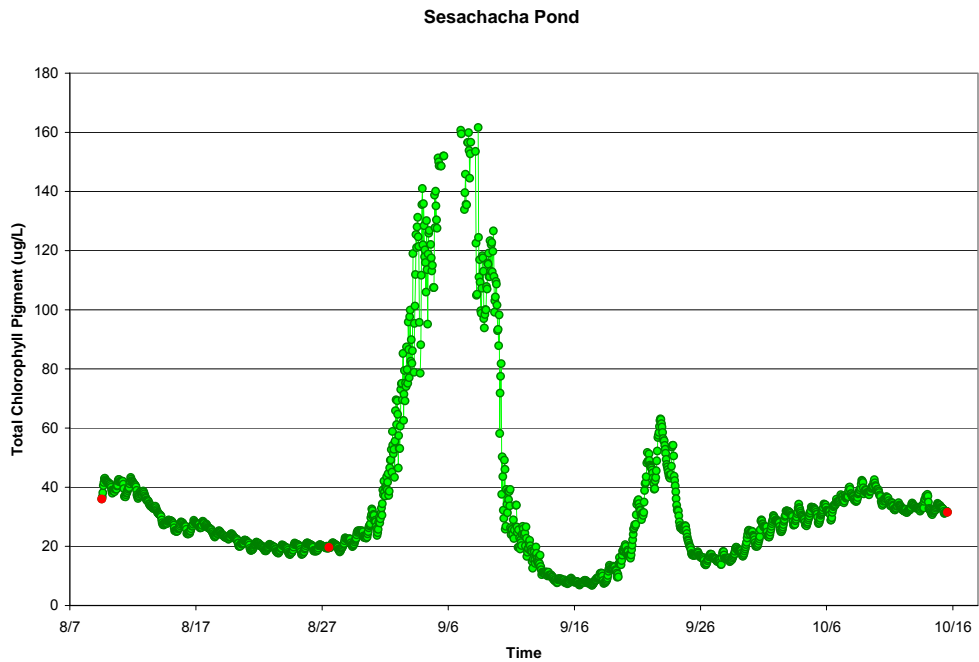
Sesachacha Pond

Figure VII-4.   Bottom water record of chlorophyll-*a* at the Sesachacha Pond station, summer 2002. Calibration samples represented as red dots.

Table VII-1.	Percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels.

Massachusetts Estuaries Project Town of Nantucket: 2002	Dissolved Oxygen: Continuous Record, Summer 2002				
	Deployment Days	< 6 mg/L (% of days)	< 5 mg/L (% of days)	< 4 mg/L (% of days)	< 3 mg/L (% of days)
Sesachacha Pond	67.1	33%	21%	10%	5%

Table VII-2.	Duration (% of deployment time) that chlorophyll a levels exceed various benchmark levels within the embayment system. "Mean" represents the average duration of each event over the benchmark level and "S.D." its standard deviation. Data collected by the Coastal Systems Program, SMAST.

Embayment System	Start Date	End Date	Total Deployment (Days)	> 5 ug/L Duration (Days)	> 10 ug/L Duration (Days)	> 15 ug/L Duration (Days)	> 20 ug/L Duration (Days)	> 25 ug/L Duration (Days)
Sesachacha Pond	8/9/2002	10/15/2002	67.1	96%	90%	86%	71%	55%
		Mean		4.62	2.87	2.30	1.44	1.12
		S.D.		10.72	7.53	5.89	3.24	2.59

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Recent eelgrass surveys were not undertaken for the Sesachacha Pond system by the MassDEP Eelgrass Mapping Program (C.Costello), as the pond is a closed system and generally a brackish environment not supportive of eelgrass. In an attempt to determine whether or not there may have been eelgrass in Sesachacha Pond as far back as 1951, analysis of available aerial photos from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. Unfortunately, the 1951 aerial photographs were uninterpretable due to image quality and it was not possible to ascertain whether eelgrass was present in the pond at that time. Nevertheless, presence of eelgrass in Sesachacha Pond is not likely as the Pond has been closed as far back as the 1930's with barrier beach openings only occurring once or twice per year.

Eelgrass surveys were conducted in Sesachacha Pond by MEP Technical Team members now at SMAST in both 1988 and 2002. In both cases grab samples of the bottom and visual surveys by SCUBA divers in multiple transects across the Pond did not reveal the presence of eelgrass. This is not surprising as the salinity in 1988 -1989 was ~2 ppt, below the level thought to support eelgrass. It is likely that eelgrass in this system is limited both by the depth of the basin (>6m) and the historic freshening of pond waters. However, at the present time the eutrophic conditions extant in Sesachacha Pond would almost certainly preclude the survival of eelgrass.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 15 locations throughout the Sesachacha Pond System (Figure VII-5). In some cases multiple assays were conducted. In all areas and particularly those that do not support eelgrass beds (such as Sesachacha Pond), benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the lack of eelgrass beds, high chlorophyll levels and low dissolved oxygen concentrations, the Sesachacha Pond System is clearly impaired by nutrient enrichment, primarily from the lack of circulation and tidal exchange. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Section VIII).

Analysis of the evenness and diversity of the benthic animal communities was also used to support the density data and the natural history information. The evenness statistic can range from 0-1 (one being most even), while the diversity index does not have a theoretical upper limit. The highest quality habitat areas, as shown by the oxygen and chlorophyll records and eelgrass coverage, have the highest diversity (generally >3) and evenness (~0.7). The converse is also true, with poorest habitat quality found where diversity is <1 and evenness is <0.5.

The Infauna Study indicated that Sesachacha Pond is presently supporting significantly to severely degraded benthic infauna habitat quality (Table VII-3). 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.

Figure VII-5.   Aerial photograph of the Sesachacha Pond system showing location of benthic infaunal sampling stations (red symbol). Station 1 in each of the transects is at the southern end of the pond (bottom).

Table VII-3.   Benthic infaunal community data for the Sesachacha Pond embayment system. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations.   Samples represent surface area of 0.018 m2, N/A indicates that numbers of individuals prevent calculation of species numbers @ 75 individuals.

Sub-Embayment	Location	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Sesachacha Pond						
East Transect	Sta. A-1	10	302	6.2	1.11	0.33
	Sta. A-2	6	530	4.3	0.54	0.21
	Sta. A-3	2	293	1.3	0.03	0.03
	Sta. A-4	2	379	1.4	0.05	0.05
	Sta. A-5	5	595	2.6	0.24	0.10
West Outer	Sta. B-1	3	32	N/A	1.50	0.95
	Sta. B-2	2	32	N/A	1.00	1.00
	Sta. B-3	4	72	N/A	1.45	0.72
	Sta. B-4	2	16	N/A	1.00	1.00
	Sta. B-5	4	72	N/A	1.66	0.83
West Nearshore	Sta. C-1	4	224	4.0	1.43	0.71
	Sta. C-2	4	288	4.0	1.34	0.67
	Sta. C-3	4	176	4.0	1.82	0.91
	Sta. C-4	3	290	2.5	0.56	0.35
	Sta. C-5	4	70	N/A	1.22	0.61

VIII. CRITICAL NUTRIENT THRESHOLD DETERMINATION AND DEVELOPMENT OF WATER QUALITY TARGETS

VIII.1 ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll a). Additional information on temporal changes within each sub-embayment and its watershed further strengthen the analysis. These data were collected to support threshold development for the Sesachacha Pond System by the MEP Technical Team and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the long-term baseline Water Quality Monitoring Program conducted by the Town of Nantucket with technical guidance from the Coastal Systems Program at SMAST. At present, Sesachacha Pond is showing significantly impaired to severely degraded habitat quality. All of the habitat indicators are consistent with this evaluation of the system (Chapter VII).

Eelgrass: 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.

Water Quality: 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. The oxygen data is consistent with high organic matter loads from phytoplankton production, as indicated by the observed chlorophyll a levels. Both the oxygen and chlorophyll records indicate a highly nitrogen enriched system, at levels that significantly impair ecological functions and resource value.

Infaunal Communities: Sesachacha Pond is presently supporting significantly to severely degraded benthic infauna habitat quality (Table VII-3). 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.
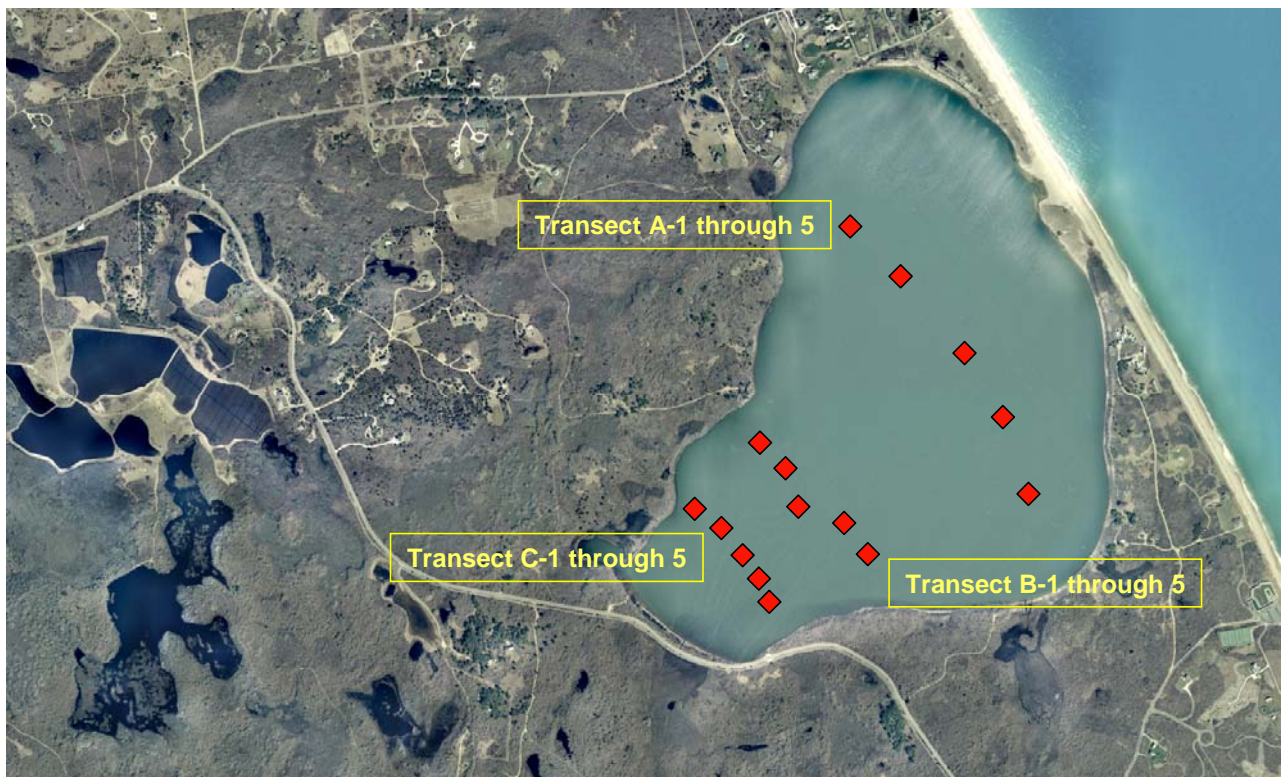
The infaunal community based classification (Table VIII-1) throughout Sesachacha Pond is fully supported by the lack of eelgrass habitat and the water quality data discussed in the text above.

Table VIII-1.	Summary of Nutrient Related Habitat Health within the Sesachacha Pond Estuary on the eastern coast of Nantucket Island within the Town of Nantucket, MA, based upon assessment data presented in Chapter VII. The system is presently structured as a great salt pond consisting of a single basin formed from seawater entry to a coastal kettle pond.
Health Indicator	**Sesachacha Pond System**
	Main Basin
Dissolved Oxygen	SI[1]
Chlorophyll	SD[2]
Macroalgae	--[3]
Eelgrass	--[4]
Infaunal Animals	SI[5]/SD[6]
Overall:	**SD**

1 – oxygen depletions frequent to 4 mg/L., and periodically to <2 mg/L.
2 – chlorophyll levels generally >20 ug/L, reaching 60 ug/l and >100 ug/L in bloom periods.
3 -- macroalgae was difficult to assess due to poor light penetration, however, large accumulations of drift algae have not been reported for this system
4 – no evidence this basin is supportive of eelgrass.
5 – main basin low numbers of species (generally <6) moderate numbers of individuals, but dominated by opportunistic species (primarily *Streblospio*).
6 – western basin (Transect B, figure VII-9) infaunal community severely depleted, low numbers of individuals (≤72) & species (≤4).

H = healthy habitat conditions; MI = Moderate Impairment; SI = Significant Impairment; SD = Severe Degradation; -- = not applicable to this estuarine reach

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

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. 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 sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved.

Within the Sesachacha Pond System the most appropriate sentinel station location is generally in the center of the basin, but given the horizontally well mixed nature of this great salt pond, Station 1 in Figure II-1 was selected as the sentinel station for threshold development. This location was selected because it is relatively deep and has prior data collection from which to assess long-term trends. As noted in previous sections, concentrations at the sentinel station approximate concentrations throughout the pond waters (i.e. it is representative of other pond locations).

Following the MEP protocol, since eelgrass has not been documented in Sesachacha Pond, restoration of infaunal habitat is the restoration goal for this aquatic system. Infaunal animal habitat is a critical resource to the Sesachacha Pond System and estuaries in general. Since the infaunal community at all sites within the Pond are either dominated by organic matter enrichment species or are depleted, comparisons to the muddy basins of other estuarine systems in the MEP region were relied upon. This analysis would suggest that a healthy infaunal habitat would clearly be achieved at an average nitrogen level of TN <0.5 mg TN L^{-1}. This level was found for Popponesset Bay where, based upon the infaunal analysis coupled with the nitrogen data (measured and modeled), nitrogen levels on the order of 0.4 to 0.5 mg TN L-1 were found supportive of high infaunal habitat quality. Similarly, in the deeper basins of Three Bays System, healthy infaunal areas are found at nitrogen levels of TN <0.42 mg TN L^{-1} (Cotuit Bay and West Bay), with moderate impairment in areas where nitrogen levels of TN >0.5 mg TN L^{-1}.

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 result is nitrogen levels reaching 1.5 mg TN L^{-1} and average TN levels of ~ 1 mg TN L^{-1}. Therefore it is not clear if average summer TN levels can be reduced to <0.5 mg L^{-1} or if this level has been achieved at any time in past centuries. The Pond was always cited to be used for shellfish transplanting and therefore likely has been somewhat nitrogen enriched, supporting moderate phytoplankton levels. Therefore, the MEP Technical Team determined that a higher TN level <0.6 mg TN L^{-1} would likely support a moderately impaired infaunal community, yet conditions that should also support shellfish. The modeling simulations in Section VIII-3 targeted the 0.5 mg TN L-1 for healthy habitat and also assessed a higher level of 0.6 mg TN L-1 for a moderately impaired condition that may be more reflective of the natural condition of this system in its present configuration. 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.

VIII.3 DEVELOPMENT OF TARGET NITROGEN LOADS

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. Throughout the 1980's, the pond was not actively managed (openings ceased), and salinities dropped as low as 2 ppt in 1989. It was in this year that the Town sought the proper environmental permits that would allow again the periodic breaching of an inlet to the Atlantic Ocean, in order to improve water quality conditions. Beginning in the early 1990's, with

the permits in place, the latest era of active management of Sesachacha Pond began. Presently, Pond water quality is managed by bi-annual breachings of the barrier beach, once each in the spring and fall (Curley, 2004). Other breaches are cut as required in order to lower the water level of Pond when it threatens lower lying properties along its shore (Conant, 2006).

Between 1967 and 2005, there have been only seven years where maximum recorded salinities have been equal to or greater than 25 ppt (see Chapter 6). Five of those years fall within the 10-year period from 1996 through 2005, which indicates that present management practices have been more effective in controlling conditions in the pond.

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.

To model the effect of adding this mid-summer breach, first, the spring-to-fall 2003 time period was modeled. This period was selected because it offers a good approximation of typical conditions with regard to the duration of the spring-time opening (6 days), water quality data was available for this period, and the average net fresh water recharge rate (2.2 ft^3/sec) could be determined by an analysis of the salinity data records from 1998, 2003, 2004 and 2005. Similar to the results of the modeled 2004 spring-to-fall season discussed in Chapter VI, Figures VIII-1 and VIII-2 show comparisons between measured data and concentrations predicted by the pond model. The resulting average modeled salinity over the whole modeled period is 24.7 ppt, and the average TN concentration is 0.87 mg/L.
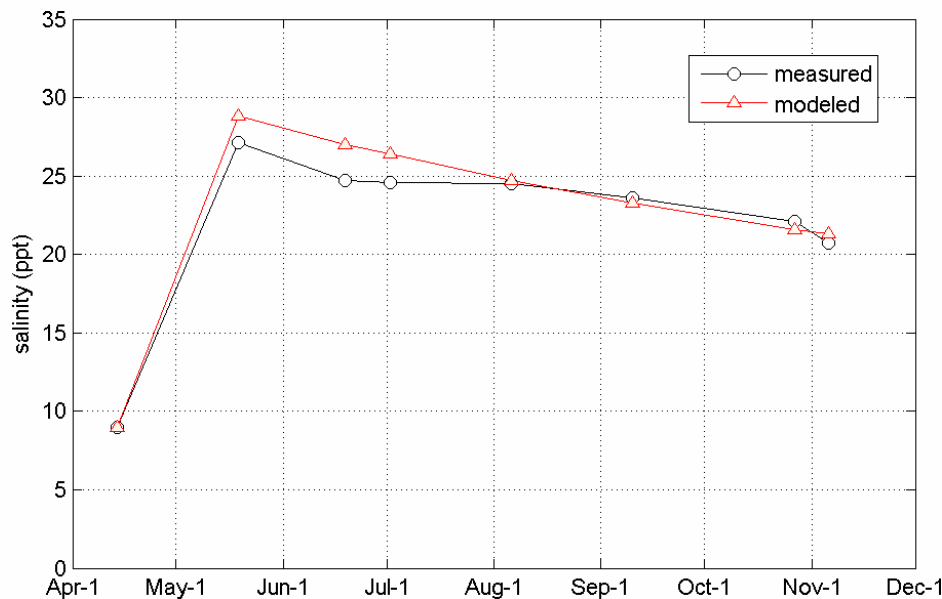

Figure VIII-1.   Comparison of measured (black circles) and modeled (red triangles) salinities through the summer of 2003 (R^2=0.74, RMS error=1.31 ppt). Present conditions with pond openings in Spring and Fall.
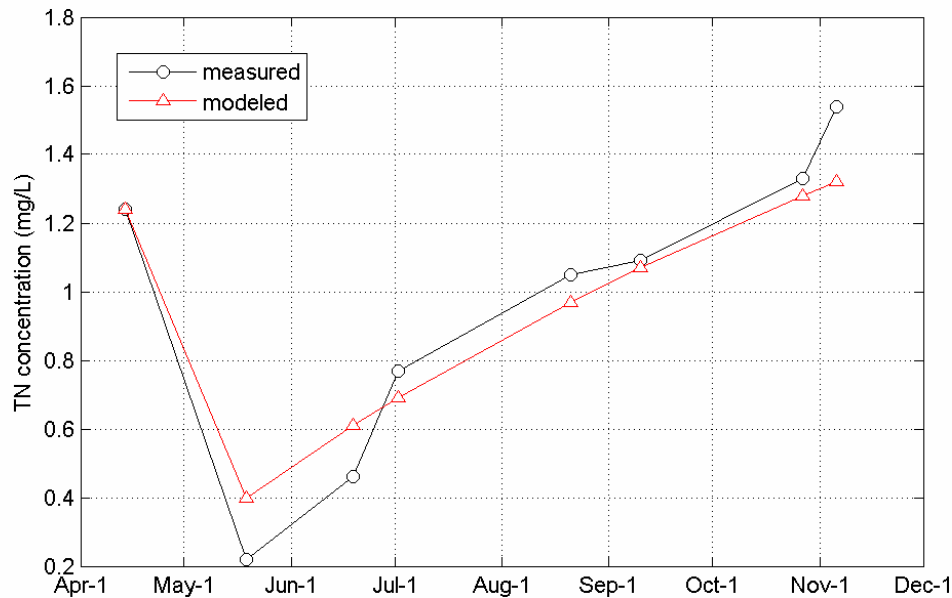
Figure VIII-2. Comparison of measured (black circles) and modeled (red triangles) TN concentrations through the summer of 2003 (R^2=0.83, RMS error=0.13 mg/L). Present conditions with pond openings in Spring and Fall.

After modeling the 2003 season, the alternative of including a mid-summer breach was modeled. For this scenario, the mid-summer breach was made 90 days after the closure of the first breach. This breach was modeled as if it were as successful as the spring 2003 breach, which lasted for six days.

A comparison of modeled salinities, showing results for runs with the mid-summer breach and without (i.e., present management practice) is presented in Figure VIII-3. After the second breach, salinities rise above 30 ppt. At the end of the simulation period, the pond salinities with the mid-summer breach are approximately 5 ppt greater then the salinities under existing management conditions (i.e. spring and fall breaches only). Both model runs include a fall breach which only draws down the pond volume, but does not permit tidal exchange with the ocean. This is the typical effect of the fall breach. The average salinity for the mid-summer breach run is 26.0 ppt, which represents an improvement of 1.3 ppt over the entire modeled period.

The attendant comparison of modeled TN is presented in Figure VIII-4. The mid-summer breach lowers TN levels by 0.50 mg/L to approximately 0.40 mg/L. At the end of the simulation period, TN concentrations are 0.4 mg/L lower after the mid-breach simulation compared to the concentrations for the simulations of existing conditions. The average TN level for the entire simulation period also drops to 0.68 mg/L, which is a substantial improvement of 0.09 mg/l over modeled 2003 average conditions.
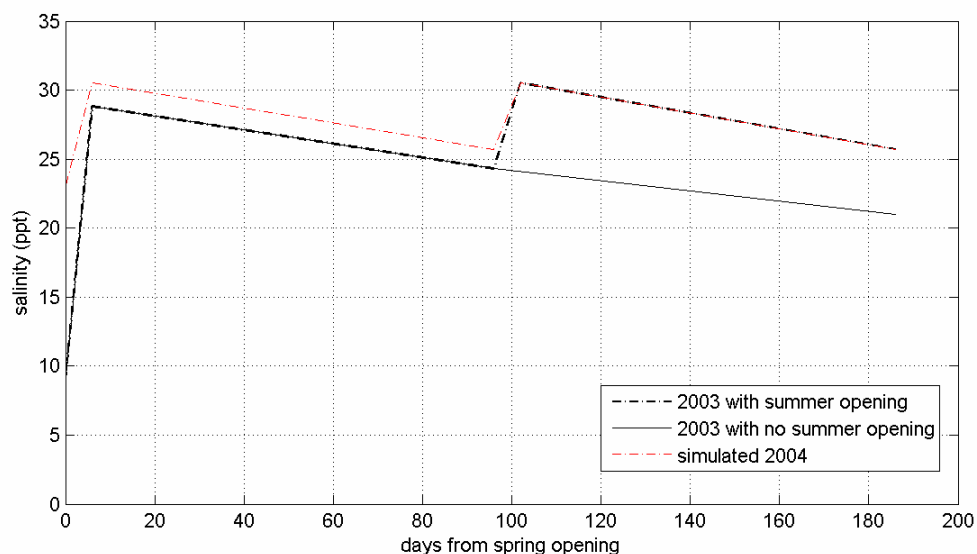
Figure VIII-3.   Comparison of modeled 2003 salinities for case where the pond is breached only in the spring (thick black dot-dashed line) and also when it is breached an additional time mid-summer. Model results for the following 2004 spring- to-fall season (thin red dash dot line) show how salinities change if the mid-summer breach is performed again.
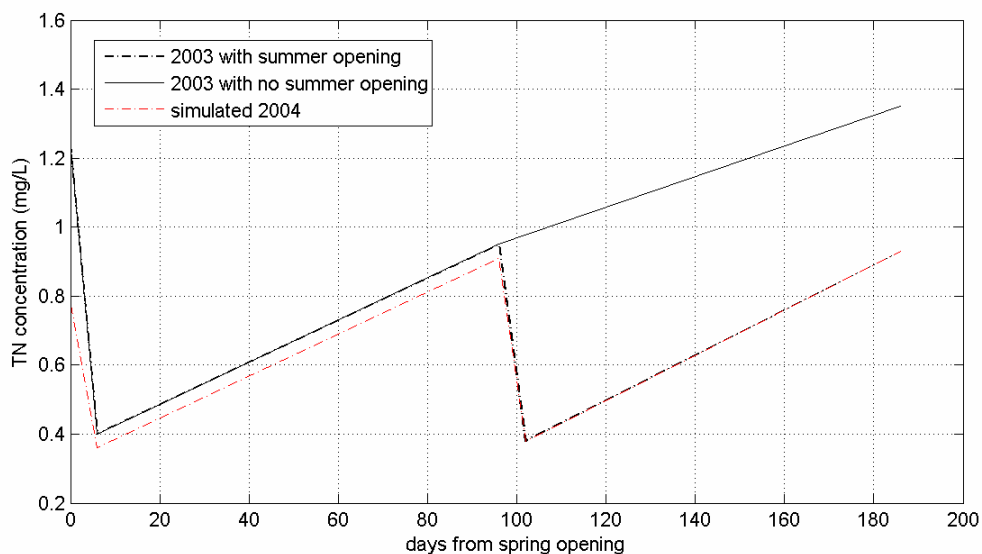
Figure VIII-4.   Comparison of modeled 2003 TN for case where the pond is breached only in the spring (thick black line) and also when it is breached an additional time mid-summer (dot-dashed line). Model results for the following 2004 spring- to-fall season (thin red dash dot line) show how TN concentrations change if the mid-summer breach is performed again.

The simulation was re-run through the same 2003 spring-to-fall period in order to investigate how the mid-summer breaching would affect water quality starting the following spring. These results are presented also in Figures VIII-3 (salinity) and VIII-4 (TN). The final salinity of the 2003 mid-summer breach is 25.7 ppt. The salinity drops through the winter to 23.3 ppt, at which point the spring (2004) breach is made. Assuming that the spring and mid-

summer breaches of the following year are as successful as the actual 2003 spring breach, the simulation shows that salinities never drop below 25 ppt after the spring, and average 27.4 ppt over the course of the entire simulation period.

A similar improvement in the TN concentration in the following year was found, with the simulated spring level set to 0.82 mg/L. This starting concentration was derived using the difference in the TN concentrations computed at the end of the 2003 simulations with and without the mid-summer breach. This difference was determined to be 0.42 mg/L, and was assumed to carry through to the simulated 2004 spring. This 0.42mg/L difference was subtracted from the measured 2003 pre-breach concentration of 1.24 mg/L to arrive at the modified starting concentration of 0.82 mg/L.. Simulation results from the second consecutive year with a mid-summer breach show that the TN concentration never rises above 1.00 mg/L, and that the average TN concentration is 0.64, which is a 0.13 mg/L improvement over average conditions computed for the 2003 season without a mid-summer breach.

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 above 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.

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