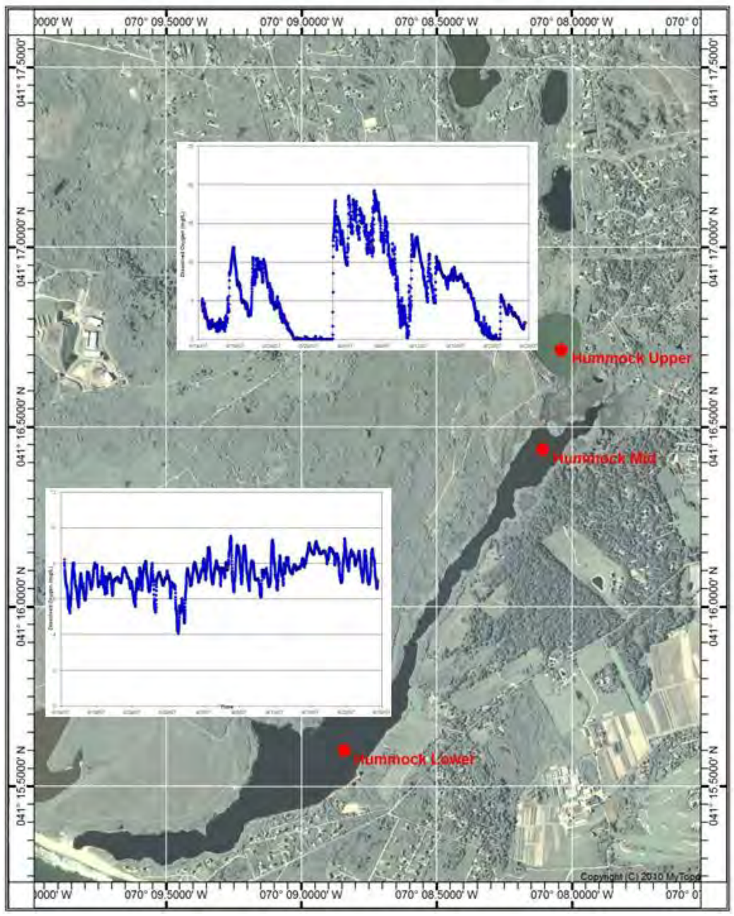
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Hummock Pond Estuarine System, Town of Nantucket, MA



University of Massachusetts Dartmouth

FINAL REPORT – January 2014

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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 Hummock Pond embayment system, a coastal embayment of the Island of Nantucket within the Town of Nantucket, Massachusetts. Analyses of the Hummock Pond embayment system was performed to assist the Town with up-coming nitrogen management decisions associated with the Towns' current update of its Comprehensive Wastewater Management Plan (CWMP), 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 analytical approach. 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 Hummock 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 Hummock 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 Hummock Pond embayment system within the Town of Nantucket is showing clear 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 gradually increasing development of the 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 Hummock Pond presently has a relatively low nitrogen load from its watershed, due to its moderately sized watershed and proportionally large undeveloped areas, it is still significantly impaired by nitrogen enrichment and is clearly eutrophic (e.g. Head of Hummock). 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 Hummock 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 Hummock Pond embayment system by using site-specific data collected by the MEP Technical Team and water quality data from the Water Quality Monitoring Program conducted by the Nantucket Marine Department and Natural Resources 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 Hummock Pond 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). MEP staff compared the Hummock Pond watershed that was approved as part of the Nantucket Water Resources Management Plan (HWH, 1990) to available information on the configuration of Hummock Pond, including the now "permanent" separation of Hummock Pond and Clark Cove into two systems, the location of the barrier beach, the wetlands in the area, water level measurements in Hummock Pond and HWH (1990) regional water table mapping. Review of the most current (1977) USGS quadrangle of the area shows Hummock Pond and Clark Cove joined near their southern ends and in the vicinity of the barrier beach. However, recent aerial photographs show that Hummock Pond and Clark Cove have been separate systems since at least March 1995 (Google Earth). Indicating that overwash from storms between 20 and 40 years B.P. filled the channel and have built a barrier to flow that will not easily be removed. Based on the review of aerial photographs, MEP staff modified the 1990 combined Hummock Pond/Clark Cove watershed to delineate a watershed to only Hummock Pond.

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 Hummock Pond (Section III); this watershed delineation was largely confirmed by subsequent water table characterizations (*e.g.*, Lurbano, 2001, Gardner and Vogel, 2005). MEP staff compared the HWH Harbor watershed to more current aerial base maps (1995 - 2012). 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 Hummock 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 Hummock 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 Hummock 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 Hummock 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 Hummock 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 Hummock Pond. One goal of this proposed management scenario is to convert the Head of Hummock into a freshwater pond year round in order to better manage water quality in the Head of Hummock Pond and also improve its function as a natural attenuator of nitrogen. Another goal is to reduce TN concentrations in the main body of Hummock Pond during the summer months, when benthic regeneration and algae production is greatest. A simple way to achieve these goals and that has been proven to be effective in other estuarine systems evaluated by the MEP is to reduce load to the pond while also modifying the breaching schedule of the pond each year (Section V and VI).

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 Hummock 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. For the current analysis, the MEP modeling team 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 with a combination of land use based N removal through elimination of wastewater from the overall watershed in combination with the separation of Head of Hummock from main Hummock Pond. These are further described at the end of Section 2 below.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Hummock 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 Hummock Pond. The current lack of eelgrass beds is expected given the high chlorophyll-*a* and low dissolved oxygen (DO) 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 Hummock 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 Hummock Pond system is currently under seasonal oxygen stress, consistent with its significant nitrogen enrichment. The oxygen records obtained from Hummock Pond show that the lower main basin of the system has moderate daily oxygen excursions, indicative of moderate nitrogen enrichment which gradually increases moving towards Head of Hummock. The evidence of oxygen levels slightly above atmospheric equilibration indicates that the main basin of the system is moderately nitrogen enriched whereas oxygen levels well above atmospheric equilibration in the Head of Hummock indicates this portion of the system is highly nitrogen enriched. However, in general in the lower portion of the main basin, the daily excursions reach upper concentrations approximating atmospheric equilibrium with a moderate number of significantly higher excursions, consistent with moderate nitrogen enrichment. Note that high levels of nitrogen enrichment can result in phytoplankton blooms that generate D.O. levels routinely in the 10-12 mg L^{-1} range or higher at mid-day as observed in the Head of Hummock.

Hummock Pond is presently supporting significantly to moderately degraded benthic infauna habitat quality. Hummock Pond is supporting a gradient in impairment from significantly impaired in the upper basin to moderately impaired in the lowest reach near the barrier beach. However, the tributary basin of Head of Hummock is currently supporting severely degraded habitat with no marine invertebrates and only 2 species of insect larvae. Head of Hummock contains lower salinity water than the Hummock Pond main basin, likely due to its function as a drowned kettle pond in the uppermost reach of the system. As such, Head of Hummock is the focus of groundwater discharge from the watershed and as the entire system is usually without tidal currents, mixing is limited. The salinity of Head of Hummock is low enough (<5 ppt) to influence the plant and animal species present, although estuarine benthic animal communities are fully capable of colonizing at salinities to 3 ppt. However, the Head of Hummock basin is virtually devoid of benthic animals, only supporting 2 insect larval species and no estuarine infauna. In contrast, the main basin of Hummock Pond, does currently support benthic animal communities, even in the same salinity range as Head of Hummock. Therefore, the loss of benthic animals in Head of Hummock appears to be related to the high organic matter loading and periodic anoxia, rather than the low salinity (as was also observed in Oyster Pond, Falmouth).

3. Conclusions of the 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 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, Hummock Pond embayment system was comprised primarily of runoff from natural surfaces, load directly to the waterbody surface, nitrogen from farm animals and wastewater nitrogen. Land-use and wastewater analysis found that generally about 81% of the controllable watershed nitrogen load to the embayment was from wastewater and 6 percent was from farm animals in the watershed.

A major finding of the MEP clearly indicates that a single total nitrogen threshold cannot be applied to Massachusetts' estuaries, based upon the results of the Nantucket Harbor analysis as well as that completed for Sesachacha Pond, Madaket Harbor and Long Pond, in addition to analyses conducted across Martha's Vineyard and Cape Cod (e.g. 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).

The threshold nitrogen level for the Hummock Pond embayment system in Nantucket was determined as follows:

Hummock 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 Hummock Pond. One goal of this proposed management scenario is to maintain the Head of Hummock Pond as a freshwater feature year round. Another goal is to reduce TN concentrations in the main basin of Hummock 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.

- A significant improvement in the nitrogen related health of Hummock 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. Total nitrogen levels within the upper basin (Head of Hummock) >1.0 mg N L^{-1} is a level associated with impoverished and degraded benthic animal habitat in other southeastern Massachusetts estuaries. Benthic communities have been found to be impaired at TN levels lower than found in Hummock Pond, e.g. Falmouth Inner Harbor, 0.58 mg TN L^{-1}, Fiddlers Cove and Rands Harbor, 0.56 mg TN L^{-1} and 0.57 mg TN L^{-1}, respectively. It appears that Hummock Pond (particularly the Head of Hummock Pond) is well beyond its threshold TN level to support healthy benthic habitat. As there is no evidence of present or historic eelgrass beds within the Hummock Pond Estuary, management actions should focus on restoration of benthic animal habitat.

- A sentinel station was established for the Hummock Pond Estuary for development of a nitrogen threshold target that when met will restore benthic animal habitat throughout its estuarine reach. Since there is a relatively small gradient in nitrogen in the main basin, the sentinel station was selected at the basin's mid-point, which reflects the average conditions within Hummock Pond. The sentinel station for Head of Hummock was established at the long-term monitoring station 3 (HUM-3). The average total nitrogen levels at the sentinel station are currently 0.72 mg N L^{-1}. It should be noted that the freshening of Head of Hummock must be managed as part of restoration of benthic animal habitat in this estuary. This TN level is comparable to other estuarine basins throughout the region that show similar levels of oxygen depletion, organic enrichment and moderately impaired benthic animal habitat. TN levels >0.70 mg N L^{-1} are generally characterized as having significantly impaired benthic habitat, phytoplankton blooms and periodic hypoxia and even fish kills (e.g. finger ponds in Falmouth). Given that in numerous estuaries it has been previously and empirically determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat (Eel Pond, Parkers River, upper Bass River, upper Great Pond, upper Three Bays, as well as the 7 inner basins of Pleasant Bay) this level is deemed most appropriate for restoration of benthic animal habitat within Hummock Pond.

- 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.

Report Recommendations

In order to ascertain how the nitrogen threshold could be attained through reductions in total nitrogen, a number of "What if" model scenarios were conducted to determine the best Nitrogen Management Plan to meet the above reductions for both units. It is important to note that the threshold scenario provided as part of this MEP assessment report is one of many possible loading and breaching combinations that could work to improve water quality in the Pond. The Draft recommendations are as follows:

Head of Hummock

With Head of Hummock evaluated as a separate unit, the plan is to isolate this portion of the Pond from the main Pond thus allowing it to return to a fresh water kettle pond. Historically, this was a separate fresh water body that was artificially connected to the main Pond. By cutting it off from the main Pond, there will be a reduction of Nitrogen to the main Pond from this severely impaired water body by 50 percent. As groundwater will continue to flow hydrogeologically through the system, some Nitrogen will continue to be fed to the main Pond, but the solution below for the main Pond will help alleviate the potential impact. Once returned to fresh water, the Head of Hummock will become phosphorous limited and more responsive to removals of said nutrient as means of controlling the observed eutrophication in that receiving water body. There are specific biogeochemical methods that have been successfully implemented in phosphorous limited impaired ponds (alum, iron, aeration, etc.) such as Ashumet Pond in the Town of Falmouth on Cape Cod and these methods can be used to “treat” the water within the Head of Hummock. Converting the Head of Hummock into a strictly freshwater pond enhances its function as a natural attenuator of nitrogen. With the recommendation to sewer the Watershed (see below), the nitrogen load flowing into the Head of Hummock will be eliminated through natural denitrification processes and prevented from entering the top portion of the main body of Hummock Pond. The amount of load that passes to Hummock Pond is controlled by the attenuating capacity of the modified fresh water basin. Based on TN attenuation observed in freshwater ponds with similar depths and retention times throughout the southeastern Massachusetts region, it is estimated that Head of Hummock would be able to attenuate upwards of 50% of the TN load entering the pond from its watershed. At present, Head of Hummock as a brackish water basin transforms significant amounts of nitrogen but ultimately passes nitrogen to the down gradient main basin. Inflowing nitrogen from the watershed will thereby be limited to those loads associated to the groundwater resources feeding into the top, middle and lower portions of the main body of the Pond.

Main Hummock Pond

With wastewater as the largest contributor, it makes sense this Report recommends reducing the wastewater that drains to the Pond from the watershed. The main goal of this proposed management scenario (wastewater related nitrogen load reduction) is to prevent time averaged pond-wide TN concentrations in the pond from rising above 0.50 mg/L in the main basin of the Pond at a sentinel station (monitoring station HUM-3) during the summer months, when benthic regeneration and algae production is greatest. A way to achieve these goals is to reduce the watershed loading to the pond, together with an additional mid-summer breach (export nitrogen). Watershed loading was reduced from present conditions until the time averaged TN concentration at sentinel station HUM-3 would remain below 0.50 mg/L during a complete breaching cycle, where the pond is open to tidal flushing for at least four days and subsequently closed for 60 days. An 82 percent reduction in wastewater is needed, but this alone will not lower water column nitrogen levels to meet the threshold set. In addition to sewering the watershed, the additional breach is also recommended. Historically, the bi-annual breaches have not been engineered to afford a tidal wash into the Pond and instead drained the Pond. The Report details the need to model a breach that will afford a tidal wash of at least four (4) days and then subsequently closed for at least 60 days.

Overall, it is important to note that the analysis of future nitrogen loading to the Hummock 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 Hummock 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 Hummock 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 nitrogen inputs and management options to negate additional future nitrogen inputs should also be considered in the context of additional breaching in order to reduce N loads and meet water quality standards for the Pond.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Hummock Pond estuary system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations.

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. (mg/L)
Hummock Pond	0.693	2.759	8.436	--	11.195	1.918	0.196	13.309	0.65-0.99	0.50
Head of Hummock	0.137	0.315	1.366	--	1.682	0.208	1.321	3.211	1.63	--
Combined Total	**0.830**	**3.074**	**9.801**	**--**	**12.877**	**2.126**	**1.517**	**16.520**	**0.65-1.63**	**0.50[8]**

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 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 2011 and 2012 data, ranges show the upper to lower regions (highest-lowest) of the sub-embayment. Individual yearly means and standard deviations in Table VI-1.
8 Average concentration through summer months at water quality monitoring station HUM-3, achieved by load reduction and successful breaching of the inlet in late spring and mid-summer.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Hummock Pond estuarine system on Nantucket Island.

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
Hummock Pond	11.195	4.446	1.918	0.109	6.473	-60.3%
Head of Hummock	1.682	0.383	0.208	0.473	1.064	-77.2%
Combined Total	**12.877**	**4.829**	**2.126**	**0.582**	**7.537**	**-62.5%**

(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.

ACKNOWLEDGMENTS

The Massachusetts Estuaries Project Technical Team would like to acknowledge the contributions of the many individuals who have worked tirelessly for the restoration and protection of the critical coastal resources of the Hummock Pond System. Without the long term efforts of these stewards, this project and other efforts to manage and restore this estuary would not be possible.

First and foremost is the significant time and effort in data collection and discussion spent by members of the Town of Nantucket Water Quality Monitoring Program conducted by the Town of Nantucket Marine Department with technical, analytical and field support from the Coastal Systems Analytical Facility at SMAST. Of particular note are Dave Fronzuto and past Coordinators, Tracey Sundell and Keith Conant and currently Ms. Tara Riley. These individuals gave of their time to collect nutrient samples from this system over many years and without this information, the present analysis would not have been possible. Similarly, we would like to thank the Hummock Pond Association for its care and concern for the pond and for providing critical information on historic surveys of aquatic vegetation. A special thank you is extended to the Board of Selectmen, Libby Gibson (Town Manager), Kara Buzanoski (Town of Nantucket, Director, Department of Public Works) and Richard Ray of the Town of Nantucket Health Department for all the assistance provided over the years thus making this report as site-specific as possible. In addition, over the years, the Town of Nantucket Shellfish and Marine Department has worked tirelessly with SMAST Coastal Systems Staff and engineers from Applied Coastal Research and Engineering towards the development of a restoration and management strategy for this system and systems island-wide. The Marine Department has also provided important support to the present MEP effort. The technical team would also like to specifically acknowledge the efforts of Cormac Collier of the Nantucket Land Council and Andrew Vorce, Director of the Nantucket Planning and Economic Development Commission for facilitating the land use analysis effort within the MEP. We would also like to thank Rosemary Blacquier (Woodard and Curran), who has been instrumental to getting this analysis funded and who has facilitated obtaining historical data sets that nobody else seemed capable of finding as well as Dr. Sarah Oktay from the University of Massachusetts-Boston, Nantucket Field Station.

In addition to numerous local contributions, technical, policy and regulatory support has been freely and graciously provided by MaryJo Feurbach and Art Clark of the USEPA; and our MassDEP colleagues: Rick Dunn, Dave DeLorenzo, Geri Lambert and Brian Dudley. We are also thankful for the long hours in the field and laboratory spent by the technical staff (Jennifer Benson, Michael Bartlett, Sara Sampieri and Dahlia Medieros), interns and students within the Coastal Systems Program at SMAST-UMD both to support the water quality monitoring program and the assessment of the estuarine resources of Hummock Pond.

Support for this project was provided entirely by the Town of Nantucket and its taxpayers as well as generous patrons of Hummock Pond, specifically Bob Williams, President of and representative for individuals of the Hummock Pond Association in addition to Cormac Collier and the Nantucket Land Council.

PROPER CITATION

Howes B.L., S. Kelley, , E.M. Eichner, R.I. Samimy, D.R. Schlezinger J. Ramsey (2013). Linked Watershed-Embayment Model to Determine the Critical Nitrogen Loading Threshold for Hummock Pond, Massachusetts. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

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I. INTRODUCTION

The Hummock Pond Embayment System is a moderately complex 142 acre estuary located entirely within the Town of Nantucket on the Island of Nantucket, Massachusetts with a southern shore bounded by water from the Atlantic Ocean (Figure I-1). Hummock Pond is generally closed to exchange with the Atlantic Ocean with the exception of periods when the barrier beach is artificially breached to create exchange with the ocean. During flooded conditions when the pond is open to the ocean, the surface area of the pond increases from ~140 acres to approximately 425 acres (Kortman and Knoecklein 1994). Though it is true that land-uses closest to an embayment generally have greater impact than those in the upper portions of the watershed, which are subject to nitrogen attenuation during transport through natural aquatic systems (e.g. ponds, rivers, wetlands etc.) prior to discharge to the embayment, effective restoration of the Hummock Pond System, will require consideration of all sources of nitrogen load. That the entirety of the watershed to the Hummock Pond system is contained within one town makes development and implementation of a comprehensive nutrient management and restoration plan for the pond more tractable as the challenges are not complicated by the municipal constraints of other towns.

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

The nature of enclosed embayments in populous regions brings two opposing elements to bear: as protected marine shoreline they are popular regions for boating, recreation, and land development; as enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shores. The number of sub-embayments (i.e. small coves) to the Hummock Pond System, while fewer than many other estuaries evaluated by the MEP in southeastern Massachusetts, greatly increases the shoreline and decreases the travel time of groundwater (and its pollutants) from the watershed recharge areas to bay regions of discharge. As such, the Hummock Pond system is particularly vulnerable to the effects of nutrient enrichment from the watershed, especially considering that circulation is mainly through wind driven mixing, the long shoreline of the pond and the only periodic flushing with "clean" Atlantic Ocean water. In particular, the Hummock Pond system and its terminal sub-embayment (Head of Hummock) along the south shore of Nantucket are at risk and already showing clear signs of eutrophication (over enrichment) from high nitrogen loads in the groundwater and runoff from the watershed and associated sub-watersheds.

The Hummock Pond Embayment System is a relatively simple coastal salt pond estuary, with a single temporary inlet, a main estuarine basin in the lower part of the system and a narrow upper section that connects to a small terminal basin referred to as the Head of Hummock. The estuary only occasionally receives tidal waters from the Atlantic Ocean based on a breaching schedule set by the Town. Floodwater from the Atlantic Ocean enters the lowermost main basin of the Pond and circulates through channels and around shallow sand spits making its way up the pond towards the narrow upper portion of the system and the Head of Hummock Pond (Figure I-2). Outflow from the pond is occasional through the barrier beach and during the periodic openings to the Atlantic Ocean.

The present Hummock Pond system results from a complex geologic history dominated by glacial processes occurring during the last glaciation of the southeastern Massachusetts region. The late Wisconsinan Laurentide ice sheet reached its maximum extent and southernmost position about 20,000 years before present (BP), as indicated by the presence of terminal moraines on Nantucket and Martha's Vineyard and the southern limit of abundant gravel on the sea floor of Nantucket Sound and Vineyard Sound (Schlee and Pratt, 1970; Oldale, 1992; Uchupi et al., 1996). The lobate ice front was comprised of the Buzzards Bay lobe that deposited the moraine along the western part of Martha's Vineyard, the Cape Cod Bay lobe that deposited the moraines across eastern Martha's Vineyard and Nantucket, and the South Channel lobe that extended east toward Georges Bank (Oldale and Barlow, 1986; Oldale, 1992). During the retreat of the ice sheet, approximately 18,000 years BP, the main part of Cape Cod was deposited as the Barnstable outwash plain and a glacial lake occupied Nantucket Sound. The glacial meltwater lake occupying what is now considered Nantucket Sound is likely to have had a profound effect on the geomorphology of Hummock Pond. The pond basin was probably formed by headward erosion by groundwater seepage fed from the glacial meltwater lake upgradient of present day Hummock Pond. The process driving the formative headward erosion of the long finger-like longitudinal basin of Hummock Pond is called spring sapping. This occurs when the water discharging from a spring to a wetland environment carries away loose sand and gravel and causes the spring and associated wetland to erode (and migrate) headward carving a long straight valley which then filled with seawater with rising sea levels post-glaciation.

The formation of the Hummock Pond System has and continues to be greatly affected by coastal processes, specifically the role that the barrier beach plays in separating the pond from Atlantic Ocean source waters. The ecological and biogeochemical structure of the pond is likely to have changed over time as the barrier beach naturally breached and closed in as a function of storm frequency and intensity. It is almost certain that its closed basin is geologically a recent phenomenon, and that the pond was more generally open during lower stands of sea level.

Figure I-2. Study region for the Massachusetts Estuaries Project analysis of the Hummock Pond Embayment System. Tidal waters enter the Pond through periodic breaching of the barrier beach and flow in from the Atlantic Ocean. Freshwaters enter from the watershed primarily through direct groundwater discharge.

The primary ecological threat to the Hummock Pond embayment system as a coastal resource is degradation resulting from nutrient enrichment. Although the watershed and the Pond have some issues relative to bacterial contamination, this does not appear to be having large ecosystem-wide impacts. Bacterial contamination causes closures of shellfish harvest areas, however and in contrast, loading of the critical eutrophying nutrient (nitrogen) to the Hummock Pond System has greatly increased island-wide over 1950 levels. Though development in the Hummock Pond watershed is limited compared to other estuarine systems on Nantucket, nitrogen loading to this system, like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater.

As way to control water quality, the Hummock Pond embayment system periodically exchanges tidal water with the Atlantic Ocean through managed "breaching" of the barrier beach (Cisco Beach). This salt pond is opened to tidal exchange by excavating a trench through the barrier beach twice per year if the water levels in the pond have risen sufficiently to provide sufficient head to erode the desired channel to the sea. In addition, to insufficient pond level, openings can be delayed due to poor hydrodynamic conditions in the near shore ocean (wave height and direction can result in rapid in filling of the temporary inlet). Typically, pond water levels of one meter or greater above mean sea level are required, before a breach is attempted. Breaching of the pond is undertaken mainly as a means of controlling salinity and nutrient levels in the pond and as a flood control measure to keep groundwater table levels low enough to keep the basements of houses bordering the pond from flooding during pond level and high water table periods of the year. Pond managers try to open the pond 2 times over the year, one opening in the fall and one opening in the spring. Typically the pond remains tidal for 5-10 days. While vigorous flushing of the pond occurs during inlet openings, pond water is continuously discharging to the ocean by pond water seepage through the barrier beach.

The Towns of southeastern Massachusetts, including those on Martha’s Vineyard and the Town of Nantucket, have been among the fastest growing towns in the Commonwealth over the past two decades and the Town of Nantucket does have a centralized wastewater treatment system that services the downtown Nantucket area with the site of discharge of its treated effluent located outside of both the Nantucket Harbor and Hummock Pond watershed. However, despite its proximity to the Nantucket wastewater treatment facility, none of the Hummock Pond watershed is connected to any municipal sewerage system. Rather, these unsewered areas rely on privately maintained septic systems for on-site treatment and disposal of wastewater. As existing and probable increasing levels of nutrients impact the coastal embayments of the Town of Nantucket, water quality degradation will accelerate, with further harm to invaluable environmental resources of the Town and the Island on the whole.

As the primary stakeholder to the Hummock Pond system, the Town of Nantucket in collaboration with the Nantucket Land Council was among the first communities to become concerned over perceived degradation of their coastal embayments. Over the years, this local concern has led to the conduct of several studies (see Chapter II) of nitrogen loading to the Hummock Pond system. Key in the Town's effort to address the impairment of local estuaries has been the Hummock Pond Water Quality Monitoring Program, spearheaded by the Town of Nantucket Marine and Coastal Resources Department and supported by private, municipal, county and state funds with technical assistance by the Coastal Systems Program at SMAST-UMD. This effort provides the quantitative water column nitrogen data (2010 and 2012) required for the implementation of the MEP’s Linked Watershed-Embayment Approach used in the present study. Additional limited water quality monitoring was undertaken in 2012 to assist in the calibration and validation of the MEP developed hydrodynamic and water quality models.

The common focus of the Town of Nantucket efforts in the Hummock Pond system has been to gather site-specific data on the current nitrogen related water quality throughout the pond system and determine its relationship to watershed nitrogen loads. 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, and previous hydrodynamic 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 complete wastewater planning and nitrogen management alternatives development needed by the Town of Nantucket.

While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management 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 volunteers over many years, most notably from members of the Marine and Coastal Resources Department. 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 nitrogen management alternatives to restore this valuable coastal resource which is currently being degraded by nitrogen overloading. It is important to note that the Hummock Pond System and its associated watershed has been significantly altered by human activities over the past ~100 years. As a result, the present nitrogen “overloading” appears to result partly from alterations to its ecological systems. These alterations subsequently affect nitrogen loading within the watershed and influence the degree to which nitrogen loads impact the estuary. Therefore, restoration of this system should focus on managing nitrogen through both management of nitrogen loading within the watershed and restoration/management of processes which serve to lessen the amount or impact of nitrogen entering the estuary.

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, 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 (MassDEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Martha’s Vineyard Commission (MVC) and the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts and the Islands.

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 MassDEP and municipalities with technical guidance to support policies on nitrogen loading to 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. In addition, each TMDL must contain an outline of an implementation plan. For this project, the MassDEP 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, MassDEP 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.

The MEP nitrogen threshold analysis 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 70 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 56 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 loading rate. 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-3). 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 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 Hummock Pond System, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer minerals (Weiskel and Howes 1992). Since even Martha's Vineyard and Cape Cod "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 1998, Weiskel and Howes 1992, Smith *et al.* 1991), Martha's Vineyard and Nantucket. 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). The estuarine reaches within the Hummock Pond System follow 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.

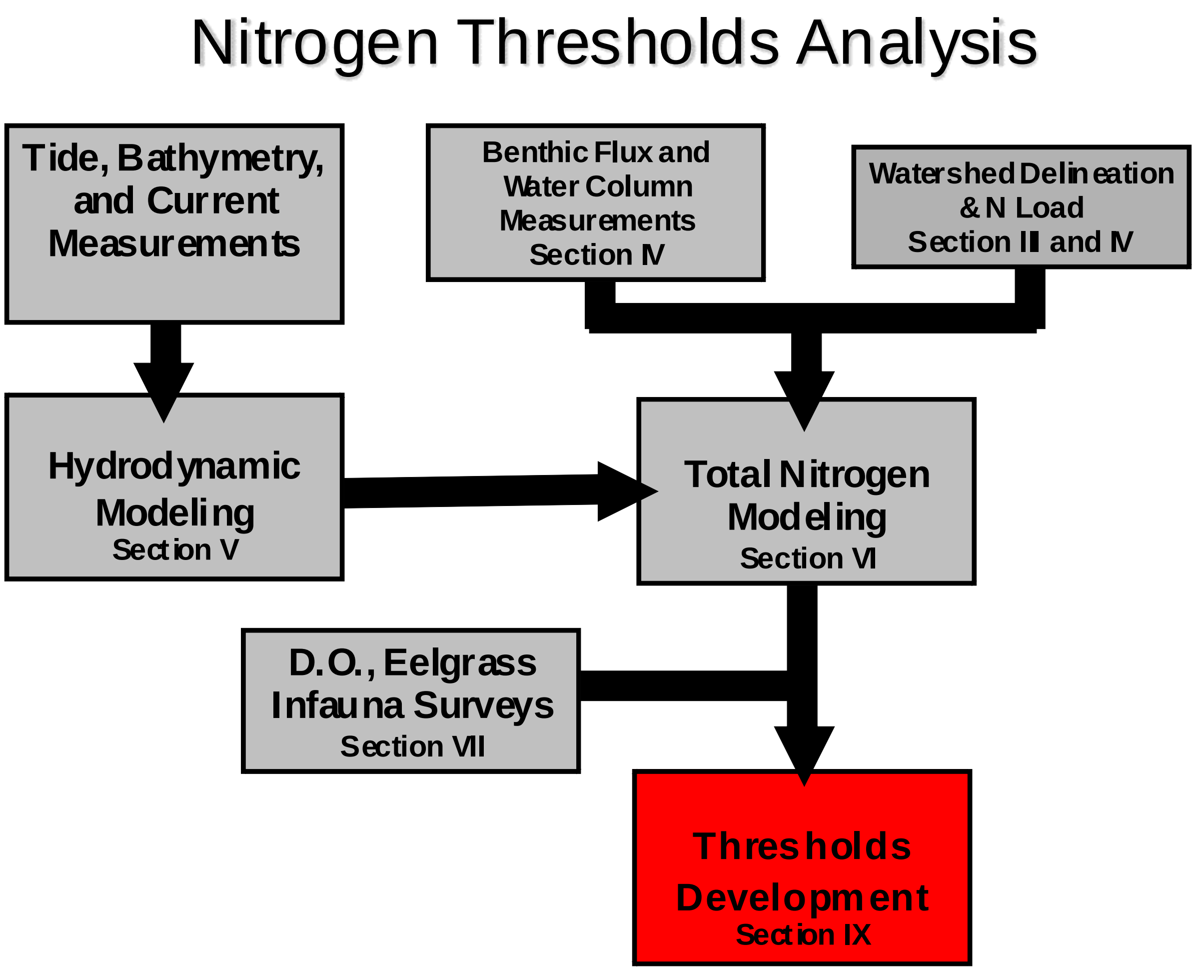

Figure I-3. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

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 and the Islands 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, MVC Water Quality Policy). 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 Hummock Pond System monitored by the Town of Nantucket Marine and Coastal Resources Department. The Water Quality Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) was utilized to "tune" general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, almost all of the estuarine reaches within the Hummock Pond System are near or beyond their ability to assimilate additional nutrients without impacting their ecological health. Nitrogen levels are elevated throughout this salt pond and nitrogen related habitat impairment within the Hummock Pond Estuary shows a gradient of high to low moving from the inland reaches (Head of Hummock) to the site of the inlet when it is created artificially at the time of a pond opening. Habitat impairment is primarily related to the configuration of the estuary and its depositional basins. The result is that nitrogen management of the Hummock Pond system is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed "eutrophication" and in certain instances can occur naturally over long periods of time. When the nutrient loading is rapid and primarily from human activities leading to changes in a coastal watershed, nutrient enrichment of coastal waters is termed "cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to the systems of Nantucket and contributed to the degradation in ecological health, the Hummock Pond basins are especially sensitive to nitrogen inputs, because of the lack of tidal exchange. The quantitative role of the tidal restriction of this system, as a natural process, was also considered in the MEP nutrient threshold analysis. 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.

I.3 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 Hummock Pond System; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within a particular system. Therefore, water quality modeling 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. The spread of pollutants may be analyzed from tidal current information developed by the numerical models.

The MEP water quality evaluation examined the potential impacts of nitrogen loading into the Hummock Pond System, including the terminal end of the estuarine system (Head of Hummock). A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents during breaching events and water elevations was employed for the overall 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 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 MEP refined watershed delineations originally developed by Horsley, Witten, Hegemann Inc. Almost all nitrogen entering the Hummock Pond System is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Atlantic Ocean source waters and throughout the Hummock Pond system were taken from the Town of Nantucket/Marine and Coastal Resources Department Water Quality Monitoring Program (a coordinated effort between the Town of Nantucket and the Coastal Systems Program at SMAST) and offshore Pleasant Bay (Cape Cod). Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of the Hummock Pond System (2010 and 2012 as well as pond opening data collected in 2012) were used to calibrate and validate the water quality model (under existing loading conditions).

I.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Hummock 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-watersheds surrounding the estuary were derived from the Nantucket Land Council database and offshore water column nitrogen values were derived from an analysis of monitoring stations in 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 II and VI. 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 infaunal analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of the Pond in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration of the Pond. This latter assessment represents only one of many solutions and is produced to assist the Town in developing a variety of alternative nitrogen management options for this system. Finally, analysis of the Hummock Pond System was undertaken relative to potential alteration of the flushing schedule to improve nitrogen related water quality. The results of the nitrogen modeling for each scenario have been presented in 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 excessive plankton and macrophyte growth, which in turn lead to reduced water clarity, organic matter enrichment of waters and sediments. This has the concomitant effect of increased rates of oxygen consumption and periodic depletion of dissolved oxygen, especially in bottom waters, as well as limiting 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 shell fisherman and to the sport-fishery and offshore fin fishery. Both the sport-fishery and the offshore fin fishery are dependant upon highly productive estuarine systems as a habitat and food resource during migration or during different phases of their life cycles. This process of degradation is generally termed "eutrophication" and in embayment systems, unlike in shallow lakes and ponds, it is not necessarily a part of the natural evolution of a system.

In most marine and estuarine systems, such as the Hummock Pond Estuary, 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. 2002).

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 estuaries and salt ponds of Nantucket, such as the Hummock Pond Estuary presently and Nantucket Harbor, Sesachacha Pond, Madaket Harbor and Long Pond, all of which have been previously evaluated by the MEP. 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.

A number of studies relating to nutrient related water quality have been conducted within the Hummock Pond System over the past two decades. Among these studies, several contained information pertinent to the MEP analytical approach and the habitat assessment for this estuary and these are described briefly below.

Town of Nantucket Water Quality Monitoring Program (2001-2007) – Over the past decade nutrient sampling of Hummock Pond has been undertaken at a variety of stations (Figure II-1a) throughout the system and primarily by the Town of Nantucket Marine Department with technical assistance from the Coastal Systems Program-SMAST. Hummock Pond has typically monitored from April to November in any of the given years, 2001-2007. Physical parameters included, temperature, dissolved oxygen, salinity, secchi disk depth, and water depth. Chemical parameters include nutrient concentrations of inorganic and organic components, Nitrate (NO3), Ammonia (NH3), Kjeldhal Nitrogen (TKN), Total Nitrogen (TN), and Total Phosphorous (TP). In 2004, 9 sampling sites were established for a study of Hummock Pond undertaken by Dr. George Knoecklein. Sites 1-6 remained the same, with a re-ordering of site 7, and the creation of sites 8, and 9. The water samples collected under this original water quality monitoring program were processed by Envirotech Laboratories located in Sandwich, MA. After review, data were used to confirm the water quality baseline for implementation of the MEP assessment and subsequent threshold development.

Implementation of the MEP's Linked Watershed-Embayment Approach incorporates the quantitative water column nitrogen data (2001-2007 including 2010 and 2012), with 2 of the 3 primary years being 2010 and 2012, gathered by the Nantucket Water Quality Monitoring Program and assays completed by the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth (ssampieri@umassd.edu) and watershed and embayment data collected by MEP staff. The MEP effort also builds upon previous watershed delineation and land-use analyses as well as historical eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Hummock Pond Estuary. The MEP has incorporated data from appropriate previous studies to enhance the determination of nitrogen thresholds for the Hummock Pond Estuary and to reduce costs of restoration for the Town of Nantucket.

Town-wide Estuarine Water Quality Assessment Report 2010 and 2012 -
Starting in 2010, the Town of Nantucket engaged directly with the Coastal Systems Program (University of Massachusetts-Dartmouth, School for Marine Science and Technology) to implement a island-wide, unified and comprehensive water quality monitoring program. The basis for the program was to address the present nutrient related ecological health issues of the salt ponds and embayments within the Town of Nantucket and to provide necessary information with which to develop policies to protect and/or remediate these systems with regard to nutrient inputs. The current water quality monitoring program is an extension of a long-term municipally coordinated monitoring effort established and coordinated through the Nantucket Marine and Coastal Resources Department in early 2000 which continued through 2007 as described above. That program was interrupted in 2008 and 2009 due to funding constraints. In 2010 it was determined that the Nantucket Island-wide Water Quality Monitoring Program should be resumed with support from the Coastal Systems Program at the University of Massachusetts-Dartmouth, School for Marine Science and Technology (SMAST). Water quality monitoring was completed during the summer of 2011 by another group, however, to maintain consistency with water quality monitoring procedures and assays from all the previous years other than 2011, water quality monitoring in 2012 was completed by the Coastal Systems Program located at the University of Massachusetts-Dartmouth, School for Marine Science.

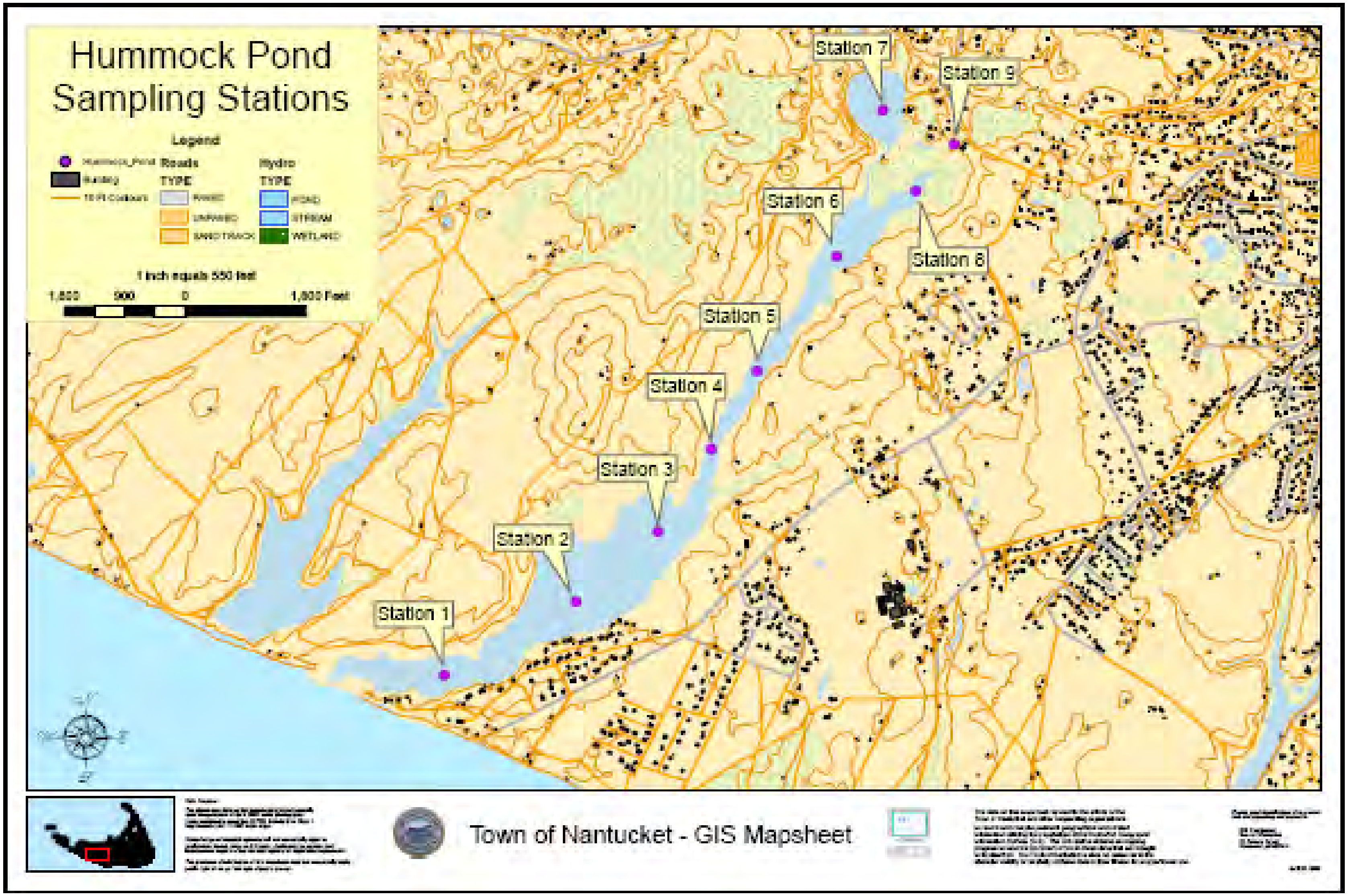

Figure II-1a. Town of Nantucket Water Quality Monitoring Program. Hummock Pond Estuarine water quality monitoring stations sampled by the Nantucket Marine Department (2002-2007).

Figure II-1b. Town of Nantucket Island-wide Water Quality Monitoring Program: Hummock Pond Estuarine water quality monitoring stations sampled by the Nantucket Marine and Coastal Resources Department (2010 and 2012).

For the 2010 and 2012 water quality assessments (Figure II-1b), CSP scientists focused primarily on the analysis of samples collected from the effort, data analysis and program coordination while the Nantucket Marine and Coastal Resources Department focused primarily on field sampling and data collection on physical parameters. Both participated in the compilation of field and laboratory data to provide an ecological overview of water quality conditions within each of the systems monitored. The goals of the monitoring program were to:

(1) determine the present ecological health of each of the main salt ponds and estuaries within the Town of Nantucket,

(2) gauge (as historical data allows) the decline or recovery of various salt ponds and embayments over the long-term (also part of TMDL compliance), and

(3) provide the foundation (and context) for detailed quantitative measures for proper nutrient and resource management, if needed.

This latter point (3) is critical for restoration planning should a system be found to be impaired or trending toward impairment.

As was the case in both 2010 and 2012, sampling took place during the warmer summer/early fall months (May-September), the critical period for environmental management. Samples were collected from 6 systems including Hummock Pond and on dates ("events") centered around worst case conditions.

The physical parameters measured in the estuaries included: total depth, Secchi depth (light penetration), temperature, conductivity/salinity (YSI meter), general weather, wind speed and direction, dissolved oxygen levels and observations of moorings, birds, shellfishing and unusual events (fish kills, algal blooms, etc). Laboratory analyses for estuaries included: salinity, nitrate + nitrite, ammonium, dissolved organic nitrogen, particulate organic carbon and nitrogen, chlorophyll *a* and pheophytin *a* and orthophosphate. For the 2010 sampling season, freshwater streams were sampled and parameters assayed included: specific conductivity, nitrate + nitrite, ammonium, dissolved organic nitrogen, particulate organic carbon and nitrogen, chlorophyll-*a* and pheophytin-*a,* orthophosphate and total phosphorus. In the summer of 2012, the water quality monitoring was focused entirely on estuarine stations. In addition, 14 sets of field duplicates were taken as part of the field sampling protocol for QA analysis. Data were compiled and reviewed by the laboratory for accuracy and evaluated to discern any possible artifacts caused by improper sampling technique.

In addition to a summary of the nutrient water quality characteristics for each estuary of Nantucket, trophic status was determined as well (including Hummock Pond). The Trophic State of an estuary is a quantitative indicator of its nutrient related ecological health and is based on concentrations of Nitrogen, Secchi Depth, lowest measured concentrations of Dissolved Oxygen (average of lowest 20% of measurements), and Chlorophyll pigments (surrogate for phytoplankton biomass). Trophic health scales generally range from Oligotrophic (healthy-low nutrient) to Mesotrophic (showing signs of deterioration of health due to nutrient enrichment) to Eutrophic (unhealthy, deteriorated condition, high nutrient). The Trophic Health Index Score used in the 2010 and 2012 Island-wide water quality assessment is a basic numerical scale based on criteria for open water embayments and uses the above mentioned measured parameters to create a habitat quality scale (Howes et al. 1999, http://www.savebuzzardsbay.org).

For the estuaries within the Town of Nantucket, a trophic index score was calculated for each sampling location using the 2010 and 2012 data. The Index scores were calculated in 2 ways, one which included the low dissolved oxygen for each year in the index and one which excluded the oxygen metric. The reason for this dual approach is that in many estuaries, such as those on Nantucket, there are only periodic depletions in bottom water dissolved oxygen, generally related to meteorological events. While these short-term depletions have important ecological consequences, they are difficult to capture in programs that sample 4 or 5 dates per summer. In these cases, inclusion of the oxygen tends to bias the Index upwards (i.e. higher quality) because of the greater probability of capturing high versus low oxygen events. This bias was found in the previous analysis of the 2010 dataset as well as the 2012 data. It should be noted that this bias relates only to the oxygen data, the other water quality parameters do not change as rapidly as dissolved oxygen and therefore the sampling program adequately captures accurate concentration data (DO changes by the hour). For the sake of completeness, the Index scores were calculated in both ways, although the scores that exclude the oxygen data appear to more accurately represent the present level of estuarine health and are more consistent with the Massachusetts Estuaries Project (MEP) assessments which include higher level measurements including long-term time series dissolved oxygen records (continuous measurements), which avoids the sampling bias issue. Data collected in 2010 and 2012 were directly applicable to the current MEP analysis of Hummock Pond.

Trophic status or nutrient related water quality for Hummock Pond based on the monitoring results showed a gradient in system health from poor quality in Head of Hummock and the upper half of Hummock Pond, to a poor to moderate quality in mid basin (Station 3), to moderate quality near the barrier beach. This gradient is similar to that observed by the MEP surveys (Section VII).

Hummock Pond Association 2006 Hummock Pond Weed Report - The purpose of this annual report was to summarize the submerged aquatic weed situation in Hummock Pond for members of the Hummock Pond Association (HPA). Monitoring and potential management of submerged aquatic weeds in the Pond has been undertaken in order to attempt to preserve the ecology and recreational uses of the Pond as well as the value of the real estate abutting the Pond. Some basic findings of the 2006 Hummock Pond Weed Report are presented directly from the report as follows:

1) It appeared that weed mass was less in 2006 than in 2005 and 2004. During the annual October weed inventory, the majority of the weeds were found in the southwestern half of the Pond. A number of factors could have been responsible for a smaller 2006 weed crop and the distribution of weeds; however, the reason(s) is not known;

2) Invasive Weed Species – Despite that fact that invasive aquatic weeds are at an epidemic level on the mainland and management of these weeds is costing individual municipal/state governments and lake/pond associations hundreds of thousand of dollars per year, invasive weed species do not yet appear to have colonized Hummock Pond;

3) Water Clarity – Water clarity in Hummock Pond is variable and influenced by algae blooms (green color), suspended solids resulting from wind/wave action and storm water runoff (cloudy brown-tan color) and tannins (dark tea colored). The Pond clarity is strongly influenced by tannins and algae at the northeast end and less so in the mid portion and southwestern end where suspended solids control the water clarity in the southwestern end of the Pond. The algae, suspended solids and tannins limit the penetration of sunlight and therefore help reduce the mass of weeds in the Pond.

The MEP reviewed the aquatic weed inventory presented in the 2006 report and can not confirm the assessment that eelgrass was identified during the 2005 and 2006 survey.

Hummock Pond Water Quality 2009: a Summary of Physical, Chemical and Biological Monitoring and Head of Hummock Pond 2010 Water Quality Program – These companion reports give results from 2009 and 2010 studies of the water quality and plankton community throughout the Hummock Pond Estuary. They were completed for the Nantucket Land Council and focused primarily on the Head of Hummock . The effort was undertaken by James W. Sutherland Ph.D. (New York State Department of Environmental Conservation (retired) and Sarah Oktay Ph.D. (University of Massachusetts-Boston, Nantucket Field Station). A primary goal of the 2010 project was to expand the four-month 2009 sampling effort and gather additional detailed information that would either confirm or refine the water quality evaluation from the previous year. In particular, the 2010 project was initiated much earlier in the season compared to 2009 so that the sequence of water quality events in HHP could be documented as the growing season progressed from the period following ice-out through late fall. A secondary goal during 2010 was to evaluate water quality in the pond prior to, and following, the spring and fall openings to the Atlantic Ocean and determine whether the opening event had a positive or negative effect on water quality.

Some general findings from the 2010 study with regards to water quality in the Head of Hummock Pond are as follows as excerpted from the report:

- HHP is categorized as a hyper-eutrophic body of water with concentrations of total phosphorus and chlorophyll a far enough beyond the eutrophic/ hyper-eutrophic boundary to be cause for concern.

- The high levels of total phosphorus measured in HHP during the growing season apparently are generated within the system, given the extreme levels of primary productivity in the form of phytoplankton biomass that sinks to the lower waters where decomposition, oxygen depletion and phosphorus mobilization can complete the remainder of the internal cycling process.

- The high seasonal concentrations of chlorophyll a measured in the HHP during 2010 and also in 2009 reflect the extensive bloom conditions of Cyanobacteria observed and measured during the two years of investigation.

- The primary source of the high total nitrogen concentrations documented in HHP during the past two years is not well understood. With such a small watershed and only a few homes within the area that contributes groundwater to the pond, it is essential that the relative contribution of internal versus external cycling of nitrogen, and possibly phosphorus, be determined for HHP before any long-term remediation is designed or implemented.

- The different Cyanobacteria populations identified in HHP during 2010 and 2009 and the intensity of the mid-summer and fall blooms during the past two years emphasize the reckless and random response of the pond to excessive nutrient concentrations and the deteriorated condition of the entire ecosystem.

- There is no ecological balance in the system; everything in the pond occurs at or toward an extreme level. The pond requires some serious remedial attention directed toward the water quality problems that continue to be manifested each year.

- Based upon the previous two years of water quality data and the recent historical information that has been collected from HHP and summarized in this report, it appears HHP has exceeded its assimilative capacity with regard to the plant nutrient nitrogen.

- A multi-faceted approach toward water quality management is required for HHP.

Regulatory Assessments of Hummock Pond Resources - The Hummock Pond System (inclusive of the Head of Hummock Pond) contains a variety of natural resources of value to the citizens of Nantucket as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP gathers the available information on these resources as part of its assessment, and presents them here (Figures II-2 through II-4) for reference by those providing stewardship for this estuary. For the Hummock Pond Estuary these include:

- Designated Shellfish Growing Area – MassDMF (Figure II-2)
- Shellfish Suitability Areas - MassDMF (not available)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-3)
- Anadromous Fish Presence (Figure II-4)

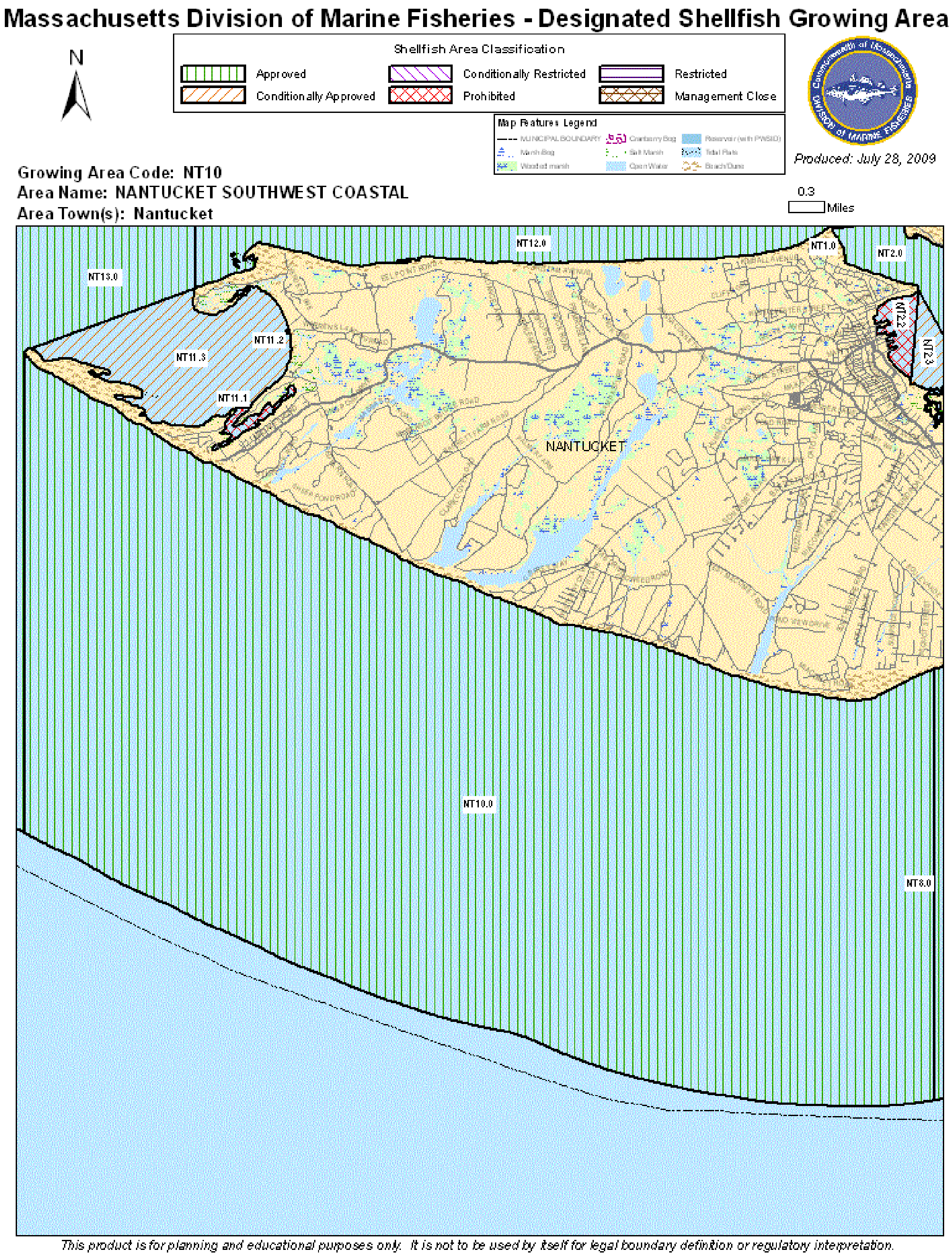

Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

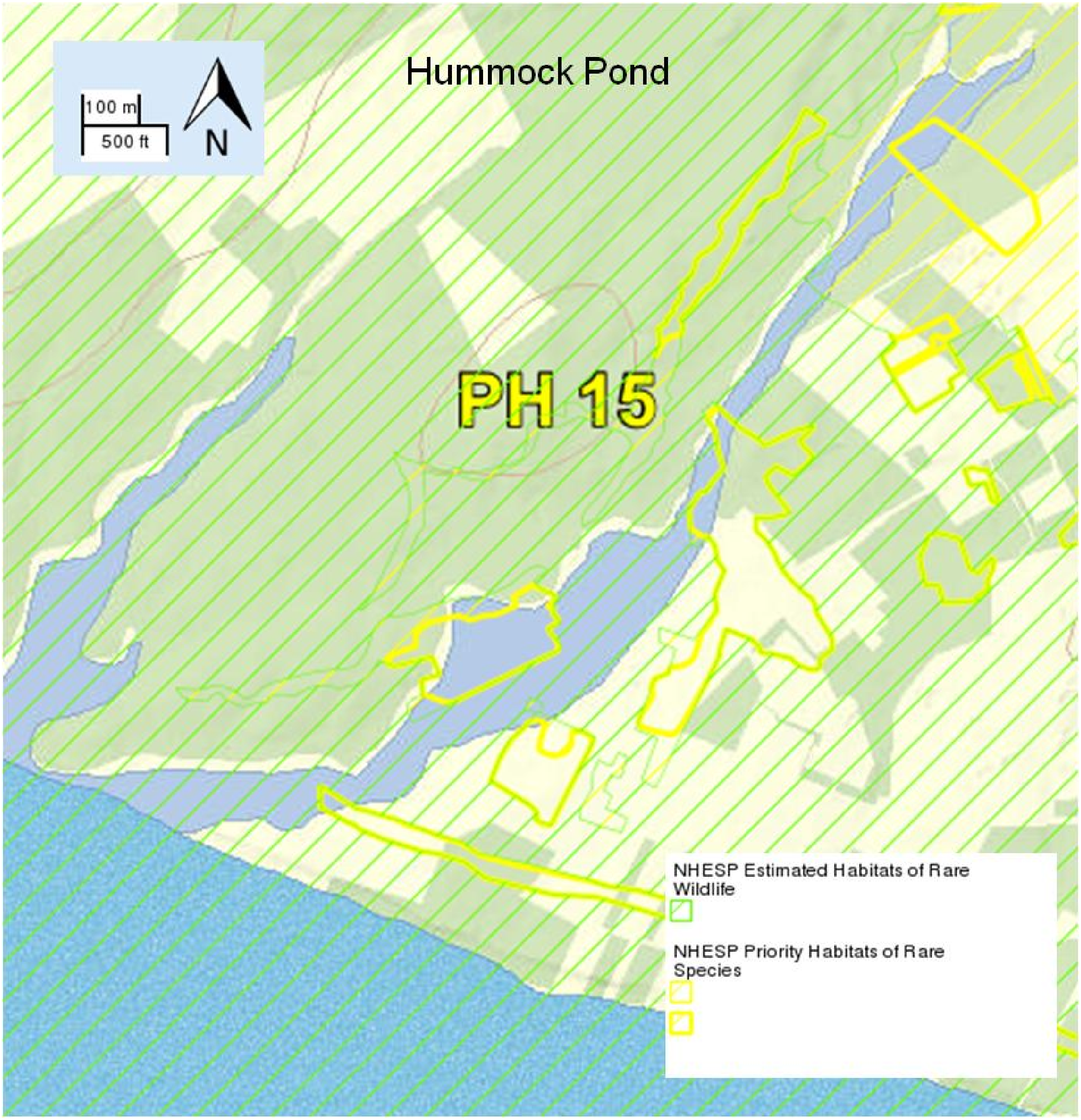

Figure II-3. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Hummock Pond Estuary as determined by the Massachusetts Natural Heritage and Endangered Species Program (NHESP).

Figure II-4. Anadromous fish run within the Hummock Pond Estuary as determined by Mass Division of Marine Fisheries. The red diamond shows area where fish were observed.

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 plain, 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 meltwater. 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) to assist in the delineation of estuary watersheds.

During the development of the Nantucket Water Resources Management Plan, an island-wide groundwater mapping project, using many of the USGS water level monitoring wells, was completed to characterize the regional, island-wide, water table configuration (HWH, 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). Subsequent water table characterizations (*e.g*., Lurbano, 2001, Gardner and Vogel, 2005) have largely confirmed the overall regional water table configuration, but refined local assessments have generally been limited by available detailed spatial data in areas dominated by extensive wetlands, such as those that surround Hummock Pond.

III.2 HUMMOCK POND CONTRIBUTORY AREAS

MEP staff produced an updated watershed to Hummock Pond based upon all available data (Figure III-1). Staff compared the Hummock Pond watershed that was approved as part of the Nantucket Water Resources Management Plan (HWH, 1990) to available information on the configuration of Hummock Pond, including the now "permanent" separation of Hummock Pond and Clark Cove into two systems, the location of the barrier beach, the wetlands in the area, water level measurements in Hummock Pond and HWH (1990) regional water table mapping. HWH delineated a watershed to a combined Hummock Pond/Clark Cove based on the 1977 USGS quadrangle of the area and a regional groundwater contour map created for the Management Plan (Figure III-2).

Review of the most current (1977) USGS quadrangle of the area shows Hummock Pond and Clark Cove joined near their southern ends and in the vicinity of the barrier beach. Historical quadrangles show that this configuration has been included in USGS maps back to at least 1893[1]. However, recent aerial photographs show that Hummock Pond and Clark Cove have been separate systems since at least March 1995 (Google Earth). Indicating that

[1] University of New Hampshire Dimond Library, http://docs.unh.edu/nhtopos/Nantucket.htm

Figure III-1. Watershed and sub-watershed delineations for the Hummock Pond estuary system. This MEP delineation is based an updated review of HWH (1990) and Town of Nantucket Watershed Protection District delineation, which has a watershed that includes both Hummock Pond and Clark Cove. MEP adjusted the watershed to include only Hummock pond and confirmed the delineation based on measured water level in the pond, wetland delineations and comparison to similar systems in the region.

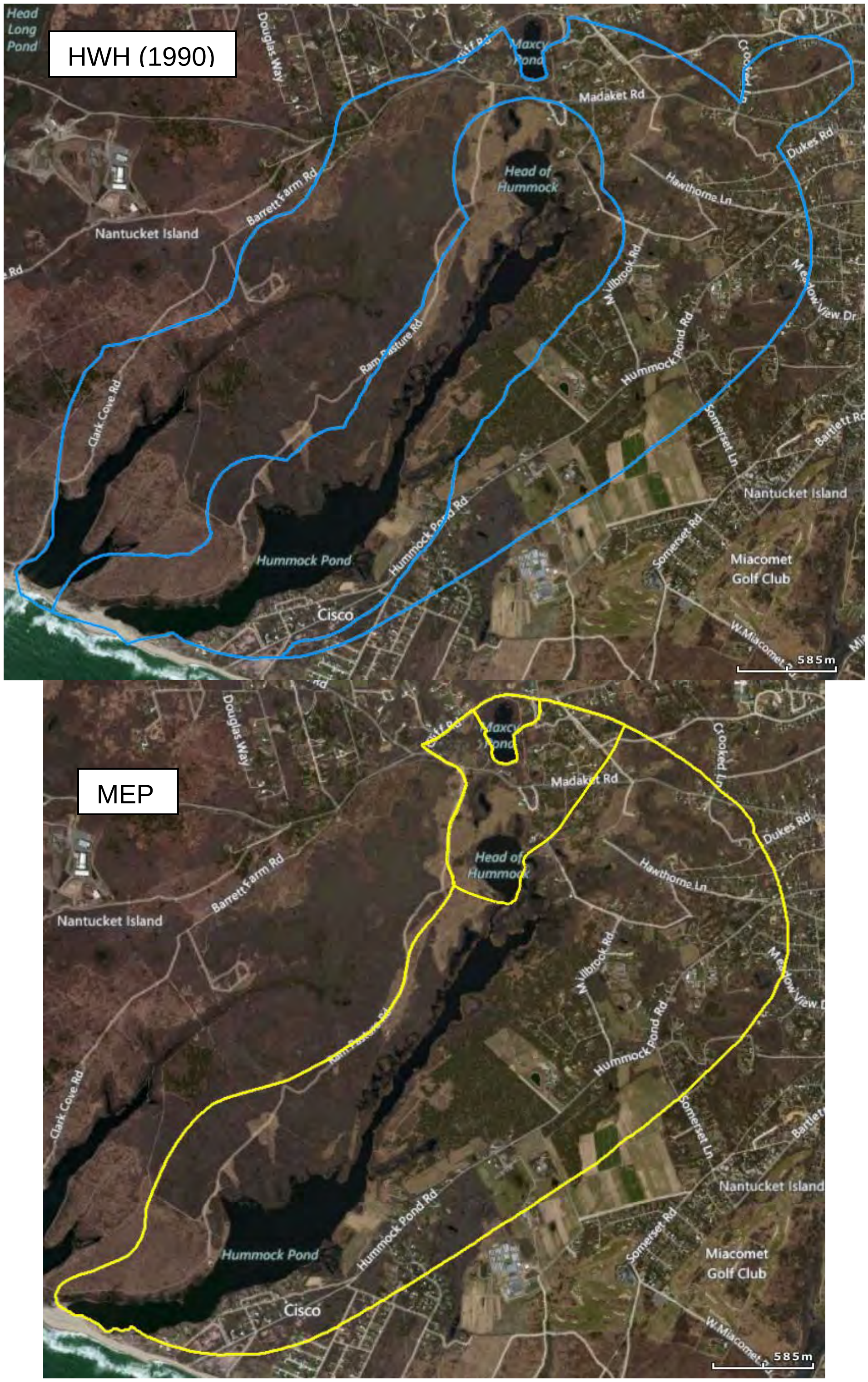

Figure III-2. Comparison of HWH and MEP Watersheds. HWH (1990) watershed includes Clark Cove and a northeastern bulge that includes a wetland system. Review of aerial photos shows that the Cove and Pond have not been hydraulically connected since at least 1995. Review of the wetlands in the upper watershed area shows a nearly radial distribution of streams around its borders, which is consistent with the HWH water table map that showed the regional groundwater divide in this area.

overwash from storms between 20 and 40 years B.P. filled the channel and have built a barrier to flow that will not easily be removed. Based on the review of aerial photographs, MEP staff modified the 1990 combined Hummock Pond/Clark Cove watershed to delineate a watershed to only Hummock Pond.

MEP staff overlaid the Town-approved Hummock Pond watershed on a March 2012 aerial base map and corrected the watershed in the following locations: 1) near the southern end where the barrier beach between Hummock Pond and the Atlantic Ocean has migrated inland (e.g. to a more northern position), 2) defined a watershed divide between Hummock Pond and Clark Cove, and 3) removed the wetland area included in the northeastern bulge of the HWH watershed based on placement of the watershed divide (see below). MEP staff also compared available water level rise from groundwater inflow information collected in Hummock Pond to water level rise in pond level predicted from watershed recharge.

Water table elevation readings were not collected in the area between Hummock Pond and Clark Cove as part of the 1990 Management Plan watershed delineation, but a significant wetland system is located in this area which includes a stream connecting it to Clark Cove. Based on this configuration and past evaluations of groundwater and wetland interactions, MEP staff excluded the wetland system from the Hummock Pond watershed. The watershed boundary between Hummock Pond and Clark Cove was drawn to follow estimated highest groundwater elevations in the upland areas between Hummock Pond and wetland areas. The northernmost portions of the updated delineation joined the HWH regional groundwater divide as shown in the Management Plan water table map.

Project staff also reviewed the wetland area included in the northeastern bulge as presented in the HWH Hummock Pond/Clark Cove watershed. The regional groundwater contours in this area would suggest that this wetland system should be on the Nantucket Sound side of the regional groundwater divide. Based on discussions with HWH staff involved in the original study, the wetland area was included based on a small stream shown on the USGS quadrangle (personal communication, Scott Horsley, Horsley Witten, 3/13). Review of this area during the MEP assessment shows that the wetland system has numerous small streams discharging in a somewhat radial pattern around the wetland, which would be consistent with it being near the top of regional groundwater divide. Based on this review, this area was excluded from the MEP Hummock Pond watershed.

In groundwater-defined watersheds, recharge within the watershed area generally matches groundwater discharge at a collection point, such as a stream or, in this case, the rise in water level of a coastal pond associated with inlet opening events. With this in mind, MEP staff reviewed the water level changes in Hummock Pond based on previous data collected by ACRE and the SMAST Coastal Systems Program. Water level data was collected in Hummock Pond during two openings of the pond to the ocean (Figure III-3). The rise in pond level which occurs after the inlet closes results from groundwater inflows. The field measurements indicate that water levels in the pond following inlet closure rose 1.27 cm/day in 2006 and 1.01 cm/day in 2012. In order to assess these changes, determinations need to be made about the area of the pond, evaporation off its surface, and any potential discharge through the barrier beach to the ocean.

The area of the pond changes as water level rise, especially since the pond is surrounded by over 50 acres of wetlands (based on MassDEP delineations), but if one adds these areas to the 174 acres of Hummock Pond surface area delineated in the same database, the resulting

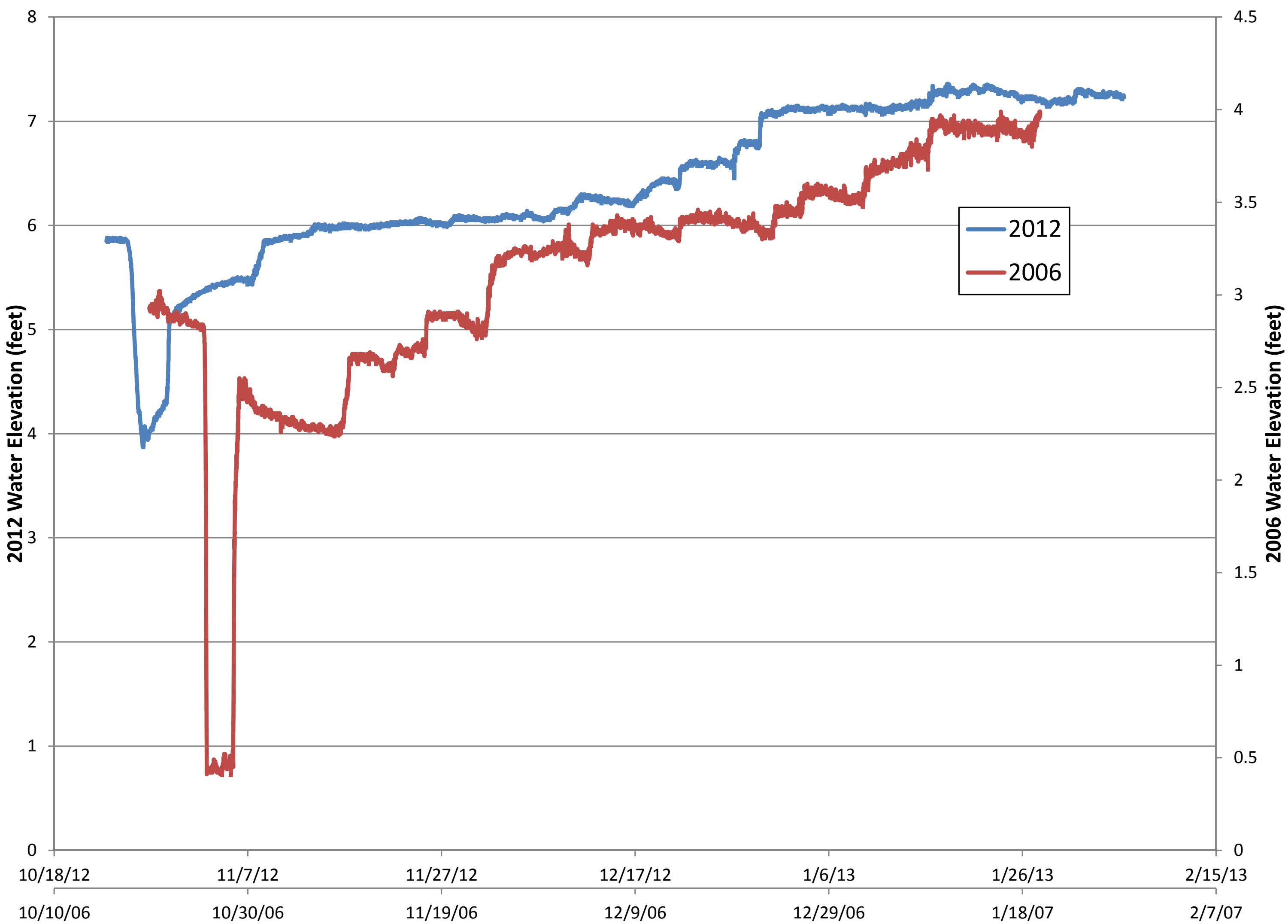

Figure III-3. Water Elevations in Hummock Pond follow 2006 and 2012 openings. Data collected by Applied Coastal Research and Engineering and the SMAST Coastal Systems Program. Change in water levels reflects groundwater discharge into Hummock Pond. Comparison of this data with the estimated inflows from the MEP watershed delineation show good agreement and reinforce the reasonableness of the watershed delineation.

flow into the pond based on the water surface elevations in 2006 and 2012 are 11,883 m3/day and 9,460 m3/day, respectively. If one then adjusts this value to account for outflow through the barrier beach (assuming a 280 m long beach, 90 m across, and an 80 m/d hydraulic conductivity), the adjusted flows into the pond are 12,716 m3/d in 2006 and 9,668 m3/d in 2012. Using the MEP watershed to Hummock Pond and a recharge rate of 27.25 inches per year, project staff estimated a groundwater discharge to Hummock Pond of 12,232 m3/d (Table III-1). Given the close agreement between the watershed estimated inflow and the estimated inflow based on changes in water levels, this analysis suggests that the MEP watershed delineation is reasonable and an appropriate basis for the MEP water quality assessment.

Overall, there are three subwatersheds delineated within the Hummock Pond system watershed: one for the freshwater pond (Maxcy Pond), one for the uppermost enclosed basin of the current estuary, Upper Hummock Pond (Head of Hummock) and one for the main estuarine basin, Lower Hummock Pond (the main basin). Table III-1 provides the daily discharge volumes for the sub-watersheds as calculated from the watershed areas and a recharge rate of 27.25 inches per year; these volumes were used to assist in the salinity calibration of the hydrodynamic model (see Section V). The MEP recharge rate used in these calculations is larger than the 18 inches per year estimated by HWH. HWH (1990) developed their recharge rate base on previous US Geological Survey estimates (*e.g.*, Knott and Olimpio, 1986). Subsequent USGS groundwater modeling on Cape Cod has shown that higher recharge rates are necessary to balance water table elevations in the most recent regional groundwater models (Walter and Whealan, 2005, Masterson, 2004). Given that Nantucket was formed during the same glacial stage as Cape Cod and is subject to largely the same weather patterns, it is reasonable to assume that the hydrogeology and recharge rates are similar. 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 Hummock Pond from the MEP delineated watershed is 12,232 m3/d.

Table III-1. Daily groundwater discharge from each of the sub-watersheds to the Hummock Pond Estuary.

Watershed	Watershed #	Discharge	
		m^3/day	ft^3/day
Maxcy Pond	1	168	5,942
Upper Hummock Pond (Head of Hummock)	2	1,158	40,879
Lower Hummock Pond (Main Basin)	3	10,906	385,142
TOTAL		12,232	431,964

NOTE: Discharge rates are based on 27.25 inches per year of recharge (Walter and Whealan, 2005).

Re-evaluation of watershed delineations for Hummock Pond allows new hydrologic data to be reviewed and incorporated where appropriate and the watershed delineation to be refined. 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 receiving aquatic systems and ultimately to the estuarine waters of the Hummock 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, the nutrient of management concern for estuarine systems is nitrogen and this is true for the Hummock 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. Permanent burial of nitrogen in the sediments 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 and the attenuation of nitrogen during transport through the watershed generally leads to errors in predicting water quality, particularly in determination of summertime nitrogen load to embayment waters.

The MEP Technical Team staff developed nitrogen-loading rates (Section IV.1) to the Hummock Pond embayment system and watershed (Section III). The Hummock Pond watershed was sub-divided to define three (3) contributing areas; one each to Maxcy Pond, a small freshwater pond in the upper watershed, one to Head of Hummock, a semi-restricted brackish sub-basin to the main basin of Hummock Pond, which also had a designated contributing area. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to each portion of the embayment.

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the estuary. This involves a review of nitrogen sources within the contributing areas, a temporal review of land use changes, the time of groundwater travel, and review of data at natural collections points, such as streams and ponds. Groundwater travel times and date built for development are not available for Hummock Pond, but the distance from the edge of the watershed to the pond surface generally is within a ten-year travel time based on a 1 ft/d flow typically assigned to outwash plain groundwater flows. In addition, review of wetlands (MassDEP coverage) show that wetlands extend into areas furthest from Hummock Pond surface; these would serve as natural collection points for groundwater discharge and shorten travel time from these furthest sections. The overall result of this review suggests that the present watershed nitrogen load should accurately reflect the present nitrogen sources discharging to the estuary. Overall and based on the review of this information, it was determined that the Hummock Pond estuary is currently in balance with its watershed load.

In order to determine nitrogen loads from the 3 contributing areas, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other detailed regional 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 subwatershed-specific land uses and pre-determined nitrogen loading rates. For the Hummock 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 parcel-specific 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. The resulting nitrogen loads represent the "potential" or unattenuated nitrogen load to each receiving embayment, since attenuation during transport is included at a later stage.

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 Hummock Pond watershed only contains one sub-watershed where natural attenuation could occur: Maxcy Pond. Nitrogen attenuation in individual ponds is generally estimated based on available information. Attenuation through the ponds is conservatively assumed to equal 50% unless available monitoring and pond physical data is reliable enough to calculate a pond-specific attenuation factor.

Smaller aquatic features do not have separate watersheds delineated, thus they are not explicitly addressed in 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.

Based upon these considerations, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for each of the 3 subwatersheds, including the one to Hummock Pond that directly discharges groundwater to the estuary. Internal nitrogen recycling was also determined throughout the estuarine reaches of the Hummock Pond 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, tax assessor's data, and other pertinent GIS data from the Town and County of Nantucket Geographic Information Systems Department (Nathan Porter, GIS Coordinator, 12/12). The land use databases contain traditional information regarding land use classifications (MADOR, 2012). Other information provided at this time, included current zoning, driveway layouts, MassGIS building footprints, and sewer districts. Digital parcels, land use/assessors data, zoning, and sewer districts are all as of October 2012.

Figure IV-1 shows the land uses within the Hummock Pond Estuary watershed area. Land uses in the study area are grouped into six land use categories: 1) residential, 2) commercial, 3) undeveloped (including residential open space), 4) public service/government, including road rights-of-way (the "900s" category), 5) agricultural, and 6) unknown (*e.g.*, parcels that do not have land use classifications in the town assessor's database). These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2012). "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.

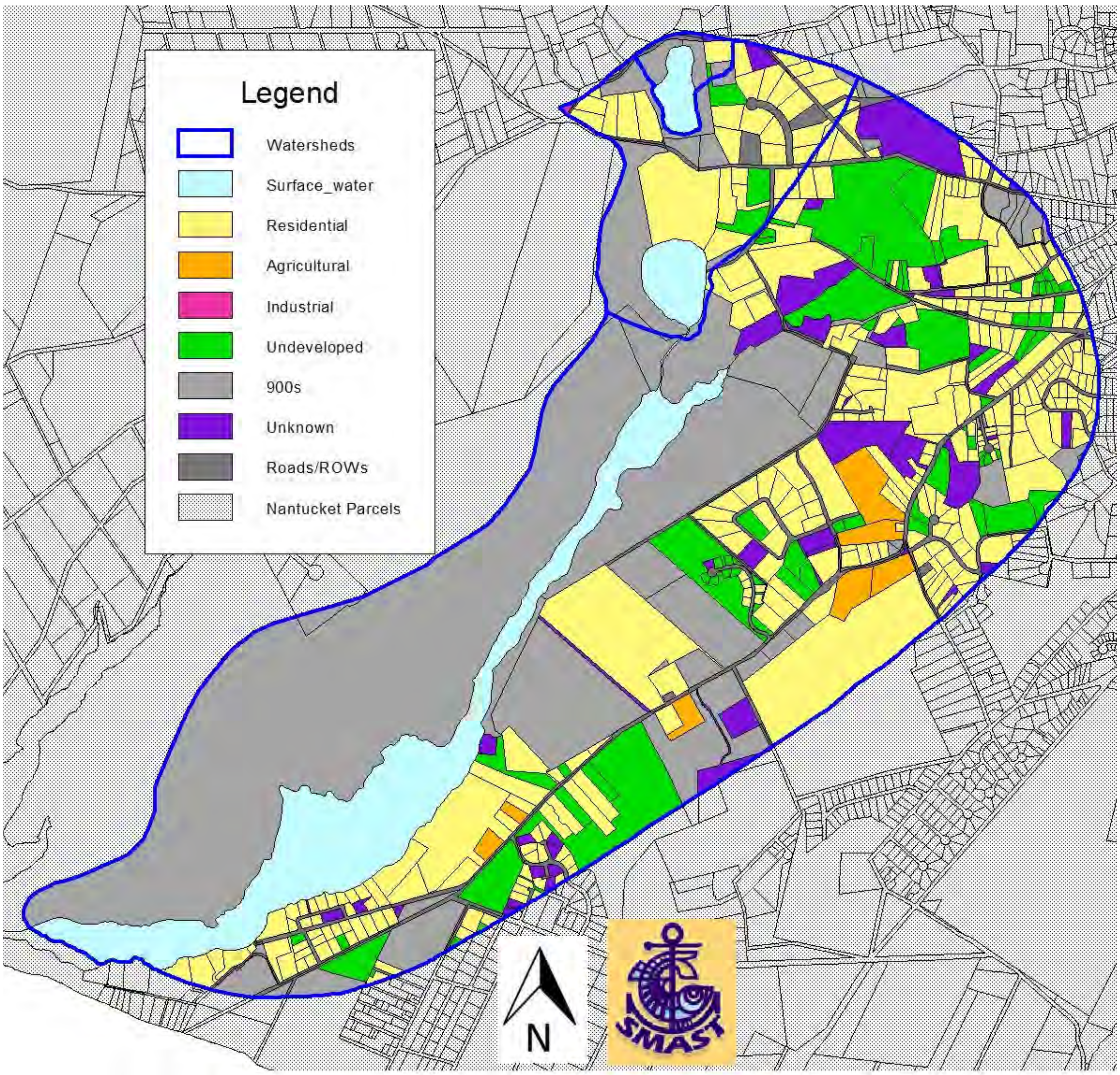

Figure IV-1. Land-use in the Hummock Pond watershed. The 3 sub-watersheds are delineated by the heavy blue line, the outer blue line encompasses the entire contributing area to the estuary. The watershed is completely contained within the Town of Nantucket. Parcels and land use classifications are based on 2012 assessor's records provided by the town and county and are grouped into the generalized categories used by MADOR (2012). Parcels in the "900s" category are lands owned by the town or non-profit entities, such as land banks or churches. Parcels in the "unknown" category do not have land use classifications in the provided town assessor's database.

In the overall Hummock Pond System watershed, the predominant land use based on area is public service (government owned lands, roads, and rights-of-way), which accounts for 44% of the watershed area; residential is the second highest percentage of the system's watershed (36%) (Figure IV-2). The high percentage of public service lands should be expected given the large Nantucket Conservation Foundation land holdings within the Hummock Pond subwatershed. Public service lands are distributed amongst each of the sub-watersheds and account for between 36%-45% of the area in each. In the Upper Hummock Pond subwatershed, public service lands are a less dominant land-use, 36% of the watershed land area, with residential land-uses being predominant, accounting for 56% of the sub-watershed land area. The watershed appears to be generally built-out with remaining undeveloped parcels accounting for only 14% of the overall watershed area.

Although the public service lands occupy the largest area within the watershed, the majority of parcels (by number) within the watershed are classified as residential uses. Of the 500 parcels within the overall Hummock Pond System watershed, 68% of the parcels are classified as residential. Among these residential parcels, single-family residences are the predominant residential parcel type (68% of all residential parcels are MADOR land use code 101). Undeveloped parcels are the next highest percentage (15%) in the watershed parcel count, while public service lands are the third highest, at 10% of the parcel count. Parcels classified as developable by the town assessor average 1.4 acres, which tends to indicate that most are isolated and developable parcels that have already been subdivided.

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 that is then linked to assessor and parcel databases using GIS techniques. MEP staff obtained three years' worth of water use for parcels within the Hummock Pond watershed from the Wannacomet Water Company (WWC)(personal communication, Linda Roberts, WWC, 5/13).

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 applied on a parcel-by-parcel basis within a watershed, where annual water meter data is linked to assessor's parcel information using GIS techniques. The parcel-specific water

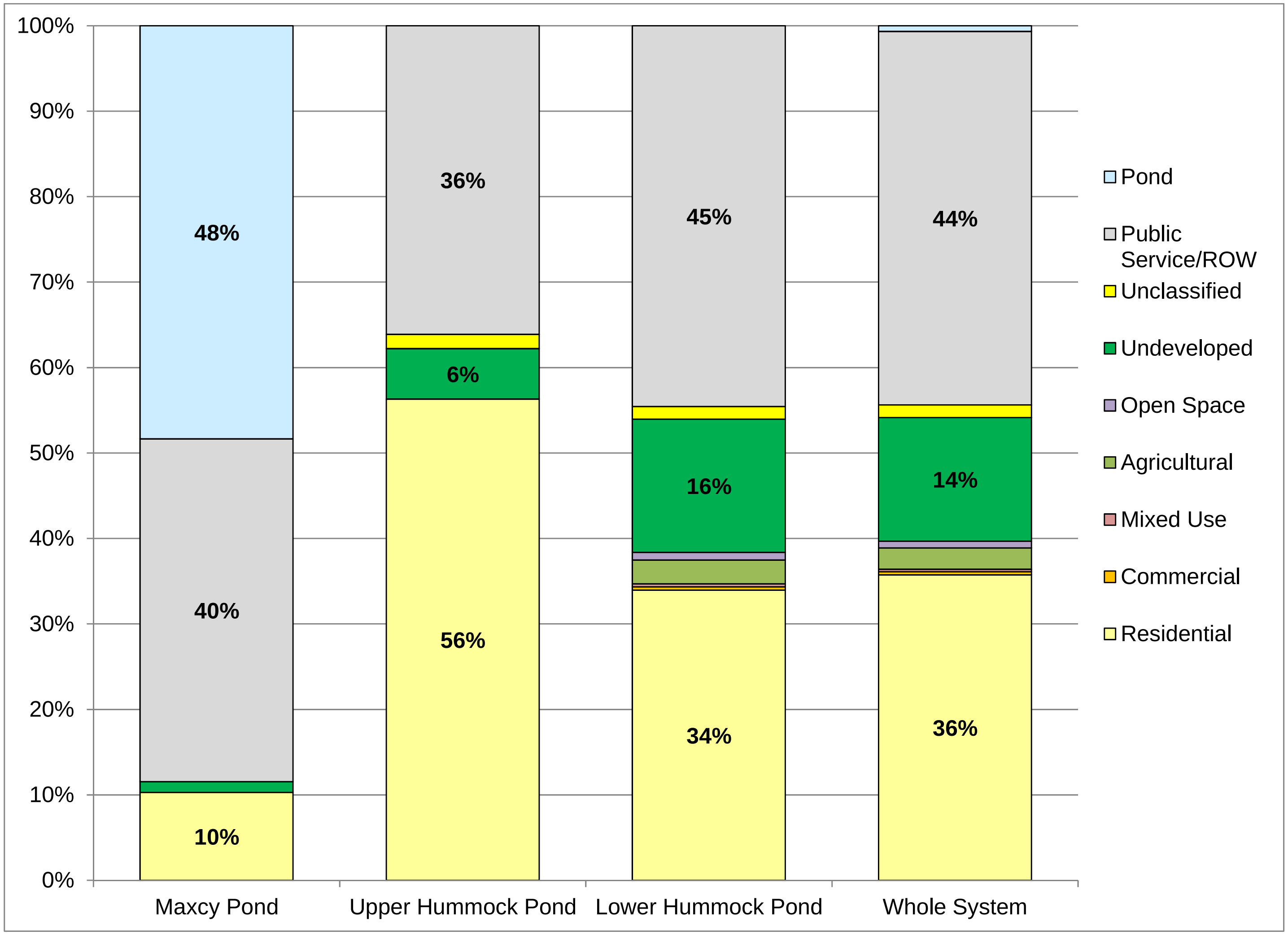

Figure IV-2. Distribution of land-uses within the 3 subwatersheds and whole system watershed to Hummock Pond. Land use categories are generally based on town assessor's land use classification and groupings recommended by MADOR (2012). Unclassified parcels do not have an assigned land use code in the town assessor's databases. Only percentages greater than or equal to 4% are labeled.

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 that 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 in similar soils 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, MEP staff has ascertained for the Estuaries Project region that while the *per capita* septic load is well constrained by direct studies, the consumptive use and nitrogen concentration data are less certain. As a result, MEP staff has derived a combined term for an 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). Further, 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 from 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 soils and 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 with other MEP Nitrogen Loading Coefficients (*e.g.*, stormwater, lawn fertilization); (c) the MEP septic nitrogen loading coefficient agrees with 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) and the reasonableness of the freshwater attenuation (Section IV.2) add 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 for septic systems 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).

Average water use was determined and assigned to individual parcels in the Hummock Pond watershed based on the three years-worth of water use data provided by the Wannacomet Water Company (WWC). Only a small portion of the Hummock Pond watershed (66 properties or 18% of the developed properties) is served by public water supply and all of these are residential properties. Using this information, average water use was developed for each residential land use code category. Developed parcels without water use accounts are assumed to utilize private, on-site wells for drinking water supply and these were assigned respective averages based on their land use classification. These averages were 225 gallons per day for single family residences (land use code 101) and 516 gpd for multi-family residences (land use code 109). The single-family residential flow was also used for the 11 non-residential properties with buildings on them with the watershed.

In order to provide an independent validation of the average residential water use within the Hummock Pond System watershed, MEP staff reviewed US Census population values for the Town of Nantucket and the US Census tract that includes most of the developed portion of the Hummock Pond watershed. 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 2010 US Census, average occupancy throughout Nantucket is 2.41 people per occupied housing unit with 36% year-round occupancy of available housing units. In contrast, Census Track 9502, which includes the watershed portion east of a line drawn through the middle of Hummock Pond and extends to the northern shore of Head of Hummock/Upper Hummock Pond, has an average occupancy of 2.57 people per occupied housing unit with a 64% year-round occupancy. If the average occupancy for the whole island is multiplied by 55 gpd, the average wastewater rate for occupied housing units is 132 gpd, while it is 141 gpd for Census Track 9502.

Neither of these estimates account of the large seasonal input, however. If it is assumed that 1) the ratio of seasonal to year-round properties listed in the 2010 Census are still representative of current conditions on Nantucket, 2) seasonal properties are occupied at the twice the average occupancy as year-round properties, 3) the higher seasonal occupancy occurs for 5 months [seen in previous Madaket Pond MEP assessment (Howes, *et al.*, 2010)] and 4) Title 5 per capita wastewater flow of 55 gpd is appropriate, the average residential unit water use for all of Nantucket would be 187 gpd and 200 gpd for the 9502 Census Track. If occupancy is triple average occupancy during the summer, the respective water use would be 242 gpd and 259 gpd. Given the measured water uses within the Hummock Pond watershed, this review suggests that the watershed has relatively high seasonal population and that this population influx during summer months accounts for the higher water-use per dwelling. This is consistent with other similar watersheds on Nantucket and Martha's Vineyard. This analysis indicates that population and water use information for the Hummock Pond watershed are in reasonable agreement and that the average annual water use is reasonably reflective of average wastewater estimates.

Nitrogen Loading Input Factors: Fertilized and Agricultural Areas

The second largest source of watershed nitrogen loading to estuaries is usually fertilized areas: lawns, golf courses, agricultural fields, and cranberry bogs. Residential lawns are usually the predominant source within this category. In order to add this source to the watershed nitrogen loading model for the Hummock Pond watershed, MEP staff reviewed available regional information about residential lawn fertilizing practices. An estimated nitrogen load is also included for agricultural areas in the watershed. The watershed does not have any golf courses or cranberry bogs.

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 nitrogen 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 in the three town survey were found to have the higher rate of fertilizer application and hence higher estimated annual contribution to groundwater of 3 lb/yr.

Nitrogen loads were also added for site-specific agricultural land uses. MEP staff reviewed all parcels classified as agricultural (700s MADOR land use codes), as well as farms on other non-farm coded properties, and determined the area of fertilized crops and obtained counts for farm animals. Nitrogen applications rates and leaching rates are the based on standard MEP agricultural crop and farm animal loading factors that have been developed for use in other MEP analyses on Nantucket. MEP staff received farm parcel-specific animal counts from the Nantucket Animal Control Officer (personal communication, Officer Gale, Nantucket Police Department, 5/13). These counts indicated the presence of horses and chickens in the Hummock Pond watershed. Species-specific nitrogen loads were developed based on USDA and other species-specific research on nitrogen manure characteristics, including leaching to groundwater. Loads were assigned to individual farm lots based on the animal counts. According to this analysis, farm animals add 276 kg/yr of nitrogen to the Hummock Pond watershed. Crop areas were determined based on review of aerial photographs. According to this review, the watershed has 140 acres of cropland. Similar to the farm animals, crop-specific nitrogen loads were developed and refined with calculations of leaching to groundwater. Based on this analysis, crops add 70 kg/yr of nitrogen to the Hummock Pond watershed.

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 utilized in the MEP-USGS groundwater modeling effort on Cape Cod (Section III). Factors used in the MEP nitrogen loading analysis for the Hummock Pond watershed are summarized in Table IV-1.

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, nitrogen loads from parcels were assigned to various watersheds based initially on whether nitrogen load source areas were located within a respective watershed. This review of individual parcels straddling watershed boundaries included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Individualized information for parcels with atypical nitrogen loading (farm animals, agricultural fields, etc.) was also assigned at this stage. 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 Hummock Pond estuary. The assignment effort was undertaken to better define the sub-embayment loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Table IV-1. Primary Nitrogen Loading Factors used in the Hummock Pond MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from watershed-specific data.

Nitrogen Concentrations:	mg/l	Recharge Rates:[1]	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 for parcels without measured water use and for buildout parcels:[2]	
Natural Area Recharge	0.072	Single family residences (land use code 101)	225 gpd
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (sq ft)	5,000	Multiple houses on same lot residential (land use code 109)	516 gpd
Residential Watershed Nitrogen Rate (lbs/1,000 sq ft)	1.08	Buildout: no commercial or industrial additions	
Nitrogen leaching rate	20%	Building area based on individual building measures	
Farm Animals[3]	kg/yr /animal	Crops[3]	kg/ha/yr
Horse	32.4	Hay, Pasture, Nursery[4]	5
Chickens	0.4	Field Crop	34
Animal N leaching rate	40%	Crop N leaching rate	30%

Notes:
1) Recharge and runoff rates based on previous assessment on Nantucket and Cape Cod groundwater modeling (Walter and Whealan, 2005).
2) Water use based on average water use for parcels with same land use classifications within the Hummock Pond watershed.
3) Crop and farm animal loading rates and leaching rates are standard MEP factors based on available literature and USDA guidance.
4) Hay, pasture, and nursery loading incorporates leaching rate.

Following the assignment of all parcels to subwatersheds, all relevant nitrogen loading data were assigned by subwatershed. This step includes summarizing water use, parcel area, frequency, private wells, and road area. Individual sub-watershed information was then integrated to create the Hummock Pond Watershed Nitrogen Loading module with summaries for each of the individual subwatersheds. The subwatersheds generally are paired with functional embayment/estuary units for the Linked Watershed-Embayment Model's water quality component.

For management purposes, the aggregated embayment watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Hummock Pond System, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), lawn fertilizers, agricultural fertilizers, farm animals, 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 contributing area of component sub-embayments, by each source category (Figure IV-3). In general, the annual watershed nitrogen

Table IV-2. Hummock Pond Nitrogen Loads. Present nitrogen loads are based on current conditions. Buildout nitrogen loads are based on the additional development allowed under current zoning at minimum lot sizes. Factors used to determine nitrogen loads are discussed in the text. Attenuation assigned to Maxcy Pond is a standard MEP assumption based on data collected from other ponds within the same eco-region. All values are kg N yr^{-1}.

		Hummock Pond N Loads by Input (kg/y):									Present N Loads			Buildout N Loads		
Watershed Name	Watershed ID#	Wastewater	Turf Fertilizers	Agricultural Fertilizers	Farm Animals	Impervious Surfaces	Water Body Surface Area	Natural Surfaces	Buildout	% of Pond Outflow	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Hummock Pond System		3,581	178	70	276	306	823	270	1,214		5,505		5,475	6,719		6,689
Maxcy Pond	1	7	0	-	-	2	48	2	-	100%	59	50%	30	59	50%	30
Upper Hummock Pond	2	495	16	10	-	40	-	23	57		584	-	584	642	0%	642
Lower Hummock Pond	3	3,079	162	61	276	264	-	245	1,156		4,086	-	4,086	5,242	-	5,242
Upper Hummock Pond Estuary Surface							76				76	-	76	76	-	76
Lower Hummock Pond Estuary Surface							700				700	-	700	700	-	700

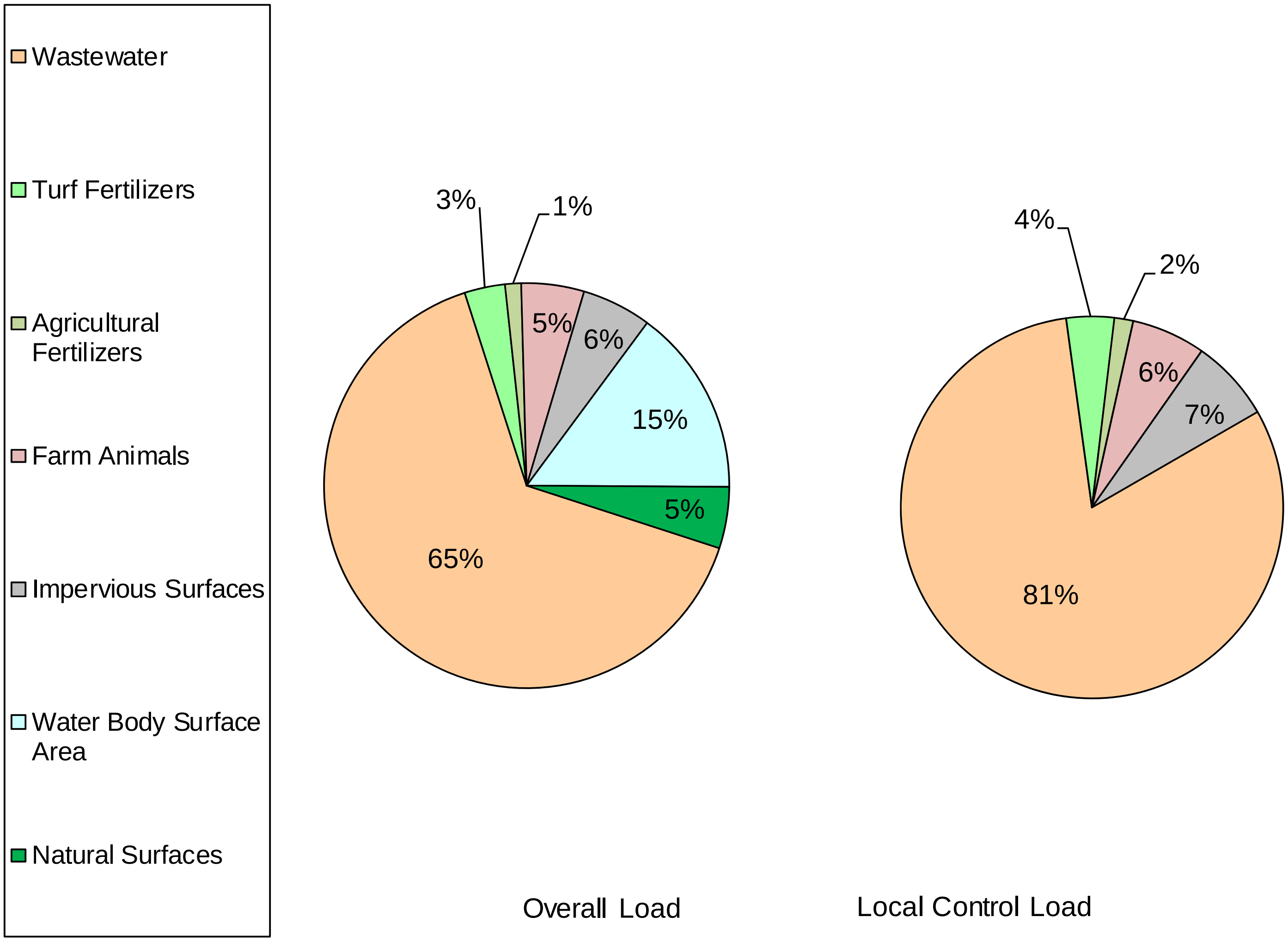

Figure IV-3. Land use-specific unattenuated nitrogen load (by percent) to the overall Hummock Pond System watershed. “Overall Load” is the total nitrogen input within the watershed, while the “Local Control Load” represents those nitrogen sources that could potentially be under local regulatory control.

input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport through streams or ponds. These attenuated loads reach the estuarine system and are used in the embayment water quality sub-model. Natural nitrogen attenuation in the Hummock Pond watershed occurs to watershed nitrogen loads that pass through Maxcy Pond.

Freshwater Pond Nitrogen Loads

Freshwater ponds are generally watershed sites of natural nitrogen reduction (or attenuation) prior to the watershed nitrogen reaching an estuary. Ponds on Cape Cod and the Islands are generally kettle hole depressions of the land surface that intercept the surrounding groundwater table revealing what some call “windows on the aquifer.” Groundwater typically flows into the pond along the upgradient shoreline, then lake water flows back into the groundwater system along the downgradient shoreline. Occasionally a pond will also have a stream outlet, which is often a herring run, that also acts as a discharge point. Since the nitrogen loads usually flow into a pond with the groundwater, the relatively more productive pond ecosystems incorporate some of the nitrogen, retain some nitrogen in the sediments, and change the nitrogen among its various oxidized and reduced forms. As a result of these interactions, some of the nitrogen entering from the pond watershed is removed prior to reaching estuarine waters, mostly through burial in pond sediments and denitrification that returns it to the atmosphere. Following these reductions, the remaining (attenuated) loads flow back into the groundwater system along the downgradient side of the pond and eventual discharge into the downgradient embayment or through a stream outlet directly to the estuary. The nitrogen load summary in Table IV-2 includes both the unattenuated (nitrogen load to each subwatershed) and attenuated nitrogen loads.

Nitrogen attenuation in freshwater ponds has generally been found to be at least 50% in MEP analyses, so a conservative attenuation rate of 50% is generally assigned to all nitrogen from freshwater pond watersheds in the watershed model unless more detailed pond monitoring or studies are available. Detailed studies of other southeastern Massachusetts freshwater systems including Ashumet Pond (AFCEE, 2000) and Agawam/Wankinco River Nitrogen Discharges (CDM, 2001) have supported a 50% attenuation factor as a reasonable, somewhat conservative rate. However, in some cases, if sufficient monitoring information is available, a pond-specific attenuation rate is incorporated into the watershed nitrogen loading modeling [*e.g.*, 87%, Mystic Lake; 40%, Middle Pond; and 52%, Hamblin Pond in the Three Bays MEP Report (Howes, *et al.*, 2006)]. In order to review whether a pond-specific nitrogen attenuation rate other than 50% should be used, the MEP Technical Team reviews the available data on each pond, including available nitrogen concentrations, impacts of sediment regeneration, temperature profiles, and bathymetric information.

Bathymetric information is generally a prerequisite for determining enhanced attenuation, since it provides the volume of the pond and, with appropriate pond nitrogen concentrations, a measure of the nitrogen mass in the water column. Combined with the watershed recharge, this information can provide a residence or turnover time that is necessary to gauge nitrogen attenuation.

In addition to bathymetry, temperature profiles are useful to help understand whether temperature stratification is occurring in a pond. If the pond has an epilimnion (*i.e.*, a well-mixed, relatively isothermic, warm, upper portion of the water column) and a hypolimnion (*i.e.*, a deeper, colder layer), the stability and volume of these two layers must be accounted for in the nitrogen attenuation calculations. In these stratified lakes, the upper epilimnion is usually the primary discharge for watershed nitrogen loads; the deeper hypolimnion generally does not interact with the upper layer. However, deep lakes with hypolimnions often also have significant sediment regeneration of nitrogen and in lakes with impaired water quality this regenerated nitrogen can impact measured nitrogen concentrations in the upper epilimnion and this impact should also be considered when estimating nitrogen attenuation.

Within the Pond study area, Maxcy Pond is the only fresh pond large enough to have a delineated watershed. MEP staff reviewed a number of sources to evaluate whether water quality samples or bathymetry had been developed for Maxcy Pond, including: 1) state Division of Fish and Wildlife pond maps, 2) the Nantucket Comprehensive Wastewater Management Plan and Final Environmental Impact Report (Earth Tech, 2004), and 3) the Nantucket Water Resources Plan (HWH, 1990). Among the reviewed sources, only HWH (1990) included any information about the water quality in Maxcy Pond and this only included results from a one-time snapshot. Based on this review, MEP concluded that there is not sufficient sampling to assign a pond-specific nitrogen attenuation rate and the standard MEP pond 50% attenuation rate was assigned to nitrogen loads from the watershed of Maxcy Pond.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development and accompanying nitrogen loads within the study area watersheds. The MEP buildout is relatively straightforward and is generally completed in four steps: 1) each residential parcel classified by the town assessor as developable is identified and divided by minimum lot sizes specified in town zoning and the resulting number of new residential units is rounded down, 2) parcels classified as developable commercial and industrial parcels by the town assessor are identified, 3) residential, commercial and industrial parcels with existing development and areas greater than twice zoning's minimum lot size are identified, divided by the minimum lot size and the resulting number of new units is rounded down, and 4) results are discussed with town staff and/or planning board members and the analysis results are modified based on local knowledge.

It should be noted that the initial MEP buildout approach is relatively simple and does not include any modifications/refinements for lot line setbacks, wetlands, road construction, frontage requirements, parcel shape requirements, or other more detailed zoning provisions. The MEP buildout approach also does not include a number of other potential impacts, including higher densities usually associated with 40B affordable housing projects or conversion of current 61A protected parcels. The fourth step, including the discussions with town planners, and, occasionally, town planning boards and wastewater consultants, usually leads to additional insights on developments that are planned, especially developments planned on government or public service parcels, and updates to assessor classifications, including lands purchased by the town as open space. This final step may lead to removal and/or additions to the number of parcels initially identified as developable and may include application of more detailed zoning provisions.

As an example of how the MEP approach might apply, assuming an 81,000 square foot lot is classified by the town assessor as a developable residential lot (land use code 130). This lot is divided by the 40,000 square foot minimum lot size specified in town zoning and the result is rounded down to two. As a result, two additional residential lots would be added to the subwatershed in the MEP buildout scenario. This addition could then be modified during discussion of town staff.

Other provisions of the MEP buildout assessment include undevelopable lots, commercial and industrial properties, and lots less than the minimum areas specified by zoning. Properties classified by the Town of Nantucket assessors as “undevelopable” (*e.g.*, MassDOR codes 132, 392, and 442) are not assigned any development at buildout (unless revised by the town review). Commercial and industrial properties classified as developable are not subdivided; the area of each parcel and the factors in Table IV-2 are used to determine a building size and wastewater flow for these properties. Pre-existing lots classified by the town assessor as developable are also treated as developable even if they are less than the minimum lot size specified in zoning; so, for example, a 10,000 square foot lot classified by the town assessor as a developable residential property (130 land use code) will be assigned an additional residential dwelling in the MEP buildout scenario even though the minimum lot size required by the zoning in the area is 40,000 square feet. Most town zoning bylaws have a lower minimum lot size for pre-existing lots (usually 5,000 square feet) that will minimize instances of regulatory takings. Existing developed residential properties that are larger than zoning’s minimum lot sizes are also assigned additional development potential only if enough area is available to accommodate at least one additional lot as specified by the zoning minimum. For the Hummock Pond MEP buildout, project staff reviewed the MassDEP wetland coverage to modify development potential on selected parcels.

Following the completion of the initial buildout assessment for the Hummock Pond watershed, MEP staff reviewed the results with town and local officials. MEP staff reviewed the preliminary watershed buildout results with Andrew Vorce, Nantucket Director of Planning, in May 2013 and received subsequent revisions from Cormac Collier, Executive Director, Nantucket Land Council in January 2014. Most suggested changes were incorporated into the final MEP buildout for Hummock Pond. Staff did not incorporate suggested changes in agricultural parcels currently classified under 61A. MEP buildouts traditionally do not include changes in these parcels because of the large variety of potential changes that could occur with their development and the uncertainty whether infrastructure changes to accommodate this load will be necessary within reasonable water quality planning horizons. If the suggested changes in 61A parcels were included, the MEP buildout load for Hummock Pond shown in Table IV-2 would increase by 7%. Water quality impacts of alternative buildouts could be assessed through town or land council developed scenarios subsequent to the MEP process.

All the parcels with additional development potential within the Hummock Pond watershed in the MEP buildout scenario are shown in Figure IV-4. Additional projected development is only residential additions; no commercial or industrial additions are projected in the MEP buildout scenario. There are projected to be an additional 149 residential units at buildout. Each additional residential property added at buildout is assigned nitrogen loads for wastewater and impervious surfaces. Residential additions also include lawn fertilizer nitrogen additions. All wastewater loads are assumed to come from standard on-site septic systems. Cumulative unattenuated buildout loads are indicated in a separate column in Table IV-3. Buildout additions within the Hummock Pond watersheds will increase the unattenuated MEP loading rate by 22%.

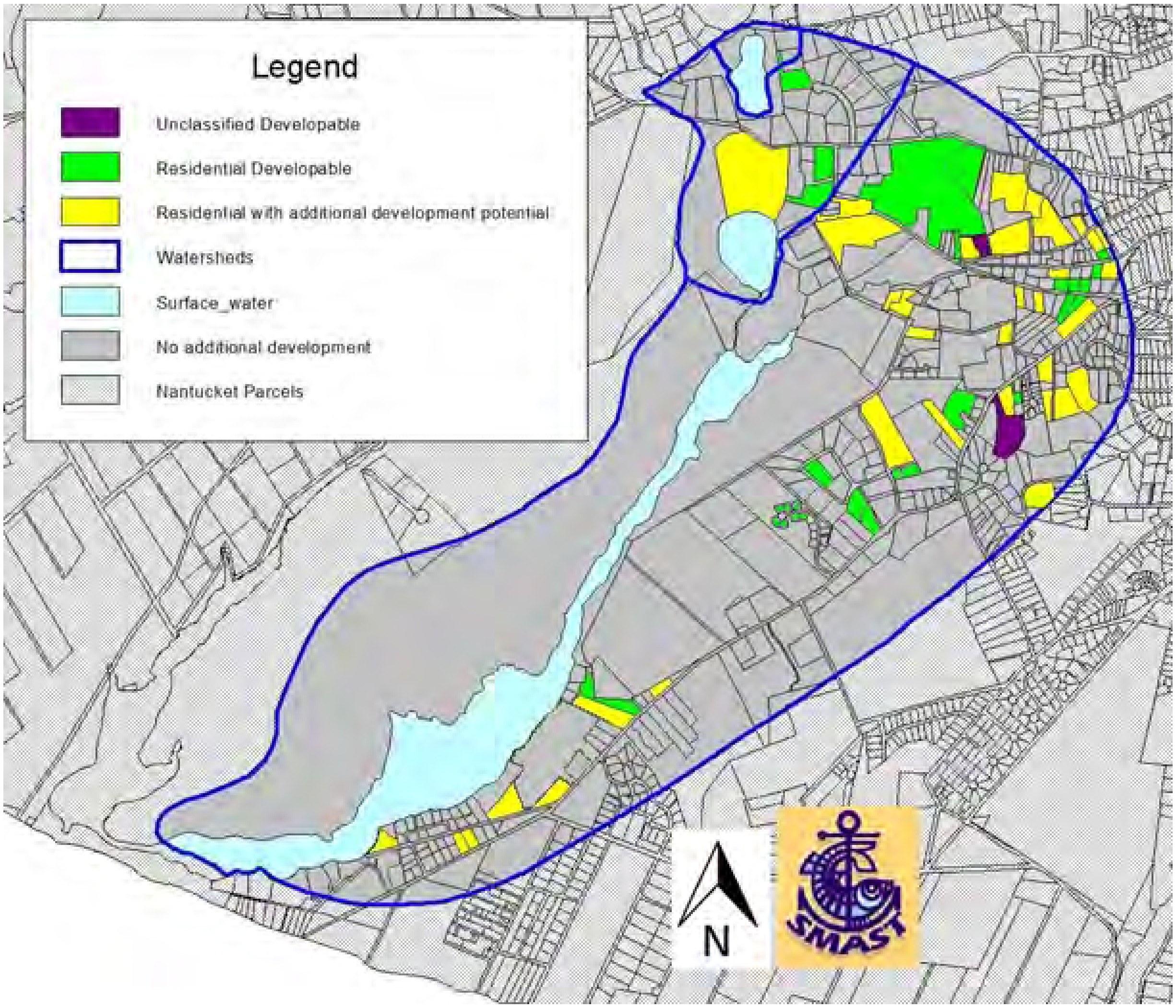

Figure IV-4. Developable Parcels in the Hummock Pond watershed. Developable parcels were determined by reviewing minimum lot sizes specified under current town zoning. Initial MEP buildout results were reviewed with the town planner and modified. Parcels colored yellow are developed residential parcels with additional development potential based on existing zoning, while parcel colored green are undeveloped parcels classified as developable for residential land uses by the town assessor. Parcels colored purple do not have assigned land use codes in the town assessor's database, but are classified as developable.

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 Hummock 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 Hummock Pond watershed with the exception of the sub-watershed to Maxcy Pond. Like most watersheds in southeastern Massachusetts, some of the watershed derived nitrogen passes 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 (e.g. Maxcy Pond) that the needed conditions for nitrogen retention and denitrification exist. As described above, nitrogen removal by the aquatic systems within Maxcy Pond prevent about ½ of the nitrogen entering the pond system from being discharged down gradient and reaching the estuary.

For the remaining bulk of the watershed, there were no significant streams or great fresh ponds and the watershed loading approach considered that nitrogen reaching the water table was transported without attenuation in the groundwater system until discharge to the estuary. A culvert was identified passing under Mill Brook Road and presumably drains Mill Brook Swamp, however, this surface water feature was intermittent and for large portions of the year there was no flow passing through the culverts under Mill Brook Road as the culverts were buried in sand. The MEP did deploy a water level logger for approximately 16 months in the small impoundment immediately up-gradient of the culvert to monitor water levels when water was present and while water levels did fluctuate, measured flows were insignificant (mean flow ~ 550 m3/d) and of little consequence as a nutrient transport mechanism when compared to the volume of groundwater and associated nitrogen load discharging directly to Hummock Pond along the shoreline.

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 Hummock Pond 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 Hummock Pond embayment system predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters when the pond is open to the Atlantic Ocean. If all of the nitrogen remained within the water column (once it entered), then predicting water column 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 down-gradient larger water body (like the Atlantic Ocean when Hummock Pond is opened). However, as is the case in Hummock 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 Hummock Pond, which only has periodic tidal exchange (in general two openings per year in the fall and the spring), the importance of nitrogen cycling in the sediments becomes a larger part of the nitrogen balance than in fully tidal systems.

IV.3.2 Method for determining sediment-water column nitrogen exchange

For the Hummock 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. Sixteen sediment samples were collected from 15 sites in Sesachacha Pond (August 2007) and incubated using a temporary field laboratory set up at a private residence adjacent to the pond to minimize transport of the cores to the field lab. 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:

Hummock Pond Benthic Nutrient Regeneration Cores

- Station Hum-1 1 core (Lower Reach; main basin)
- Station Hum-2 1 core (Lower Reach; main basin)
- Station Hum-3 1 core (Lower Reach; main basin)
- Station Hum-4 1 core (Lower Reach; main basin)
- Station Hum-5 1 core (Lower Reach; main basin)
- Station Hum-6 1 core (Lower Reach; main basin)
- Station Hum-7+8 2 cores (Lower Reach; main basin)
- Station Hum-9 1 core (Head of Hummock; deep)
- Station Hum-10 1 core (Head of Hummock; deep)
- Station Hum-11 1 core (Upper Reach; main basin)
- Station Hum-12 1 core (Upper Reach; main basin)
- Station Hum-13 1 core (Upper Reach; main basin)
- Station Hum-14 1 core (Upper Reach; main basin)
- Station Hum-15 1 core (Upper Reach; main basin)
- Station Hum-16 1 core (Lower Reach; main basin)

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-water column 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 to the pond, 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^{o}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. Hummock Pond embayment system sediment sampling sites (yellow 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.

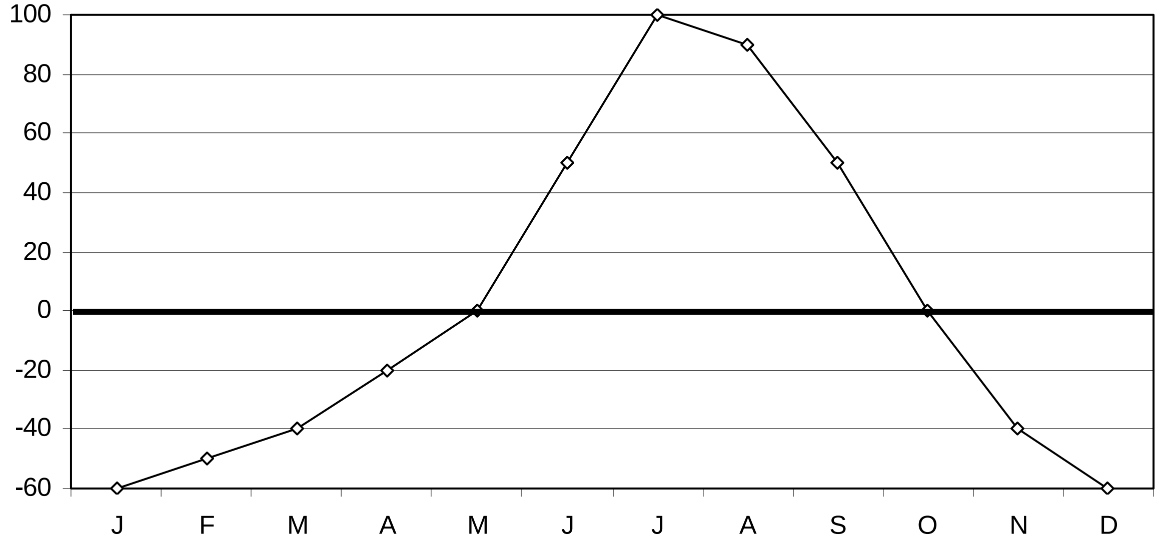

Figure IV-6. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Sediment Nitrogen Release by Standard Core Approach: Sediment sampling was conducted throughout the main basin of Hummock Pond and its upper tributary basin, Head of Hummock, 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 Hummock 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 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, (two-thirds 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 Hummock Pond (Chapter VI) are presented in Table IV-3. The general pattern is consistent with other estuaries. The relatively deep upper depositional basin of Head of Hummock showed a low-moderate net release of nitrogen. The sediments of this basin are highly organic and anoxic with periodic watercolumn hypoxia or anoxia occurring in summer. The sediment features and oxygen dynamics are consistent with the observed net nitrogen release in this basin. In contrast, the Main Basin of Hummock Pond shows only a low net rate of nitrogen release during summer. The sediments are generally oxidized at the surface and frequently sandy, consistent with the lower rate. These measured rates of nitrogen release from the sediments within the Hummock Pond System were also evaluated by comparisons to other similarly configured eutrophic basins, with comparable salinities and flushing rates, throughout the region.

The range of net nitrogen release (0.3 mg m^{-2} d^{-1} to 17.8 mg m^{-2} d^{-1}) within the Hummock Pond/Head of Hummock basins was found to be similar to other poorly flushed brackish basins throughout the MEP project region. On Nantucket, Long Pond forming the uppermost restricted basin of the Madaket Harbor/Long Pond System yielded nearly identical nitrogen flux rates, 6 mg m^{-2} d^{-1} to 14 mg m^{-2} d^{-1}, at comparable salinities. Similarly, the brackish upper reach of the Slocums River (0.6 mg m^{-2} d^{-1}) and uppermost basin of Herring River, Harwich, (9.7 mg m^{-2} d^{-1}) also had comparable rates, although under slightly higher flushing conditions. Finally, the Mill Pond basin, a tidally restricted brackish pond associated with Bass River, was found to have measured net nitrogen release rates under similar flushing and salinity conditions, 6.1 mg m^{-2} d^{-1}, while Trapps Pond of a moderate salinity and a tidally restricted pond associated with Sengekontacket Pond on Martha's Vineyard, also was found to have the same moderate rate of nitrogen release (9.2 mg m^{-2} d^{-1}) as the Hummock Pond basins. Overall, it appears that the nitrogen release rates measured throughout the Hummock Pond System are consistent with the estuaries internal environmental conditions and organic matter enrichment and have rates comparable to that found in other tidally restricted brackish water basins throughout the region. Overall, sediment nitrogen showed a clear pattern of net release with higher rates in the organic rich depositional basin of Head of Hummock Pond and lower rates from the shallow, more oxidized sediments of the main basin of Hummock Pond. The measured net nitrogen release rates were used in the nitrogen water quality modeling of the Hummock Pond System (Section VI).

Table IV-3. Rates of net nitrogen return from sediments to the overlying waters of the Hummock Pond Basins. 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

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			i.d.
	Mean	S.E.	N	
Hummock Pond				
Head of Hummock	17.8	6.4	2	Hum 9,10
Hummock Pond Main Basin	0.3	2.4	14	Hum 1-8, 11-16

Station numbers refer to Figures IV-5.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes field data collection effort and the development of hydrodynamic models for the Hummock Pond system (Figure V-1). For this system, the model offers an understanding of water movement from the pond during and after a breach. It provides the first step towards evaluating water quality, and it is 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 loading into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

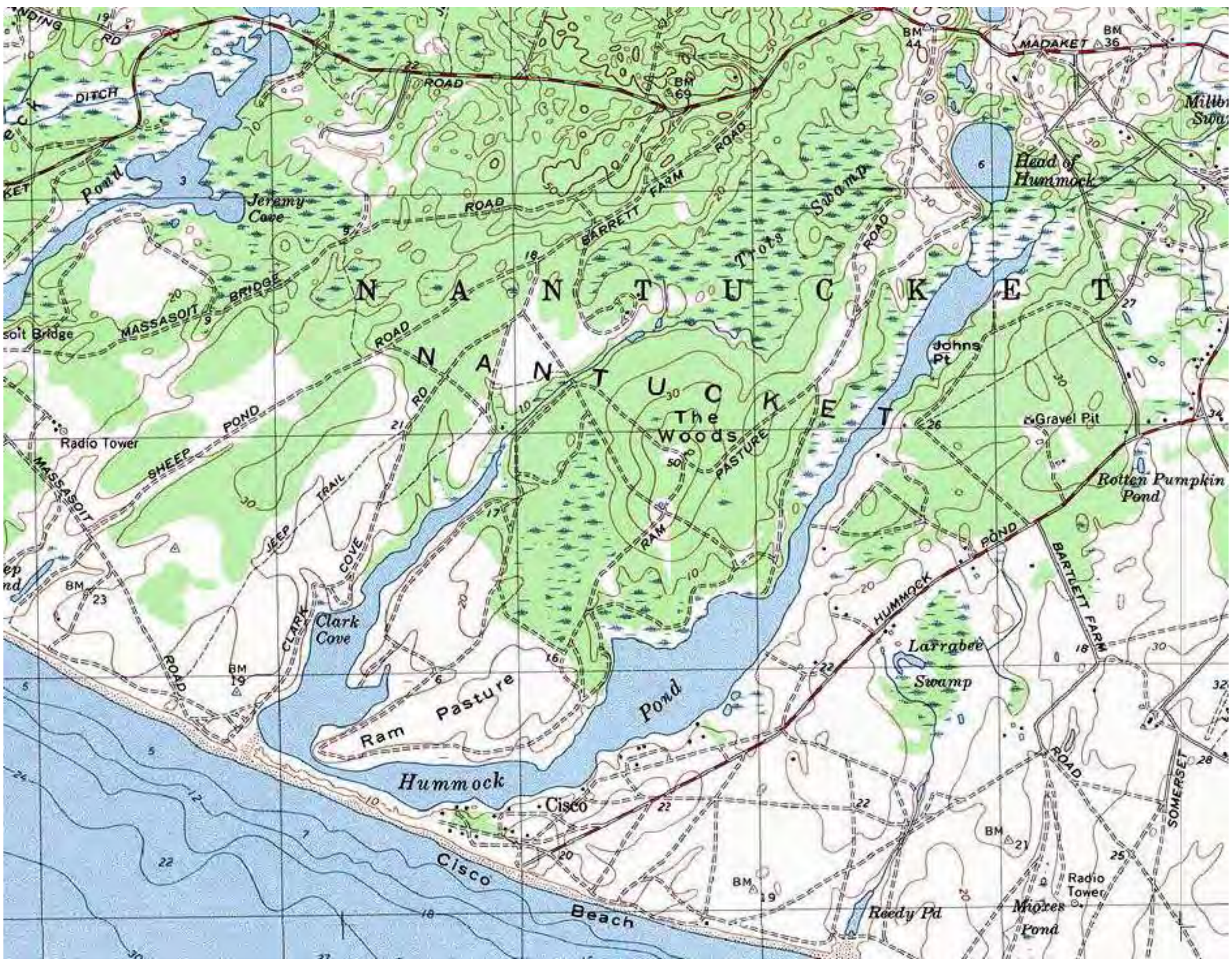

Figure V-1. Topographic map detail of Hummock Pond on the southern shore of Nantucket Island.

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 Hummock Pond are the initial recipients of freshwater flows (i.e., groundwater and surface streams) 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

Hummock Pond is set along the southwestern shoreline of Nantucket. The layout of the Hummock Pond system is shown in the topographic map detail of Figure V-1. The pond has a surface area of approximately 190 acres during times when the pond is not open to the ocean. The pond is periodically opened by means of a trench dug across the beach to drain the pond into the Atlantic Ocean.

Many other examples of systems similar to Hummock Pond, sometimes referred to as "blind", "intermittently open", or "seasonally open" estuaries, exist on Nantucket and Martha's Vineyard and are also found globally in regions of Australia, 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 affecting water quality. There is also a long history of breaching coastal ponds seasonally for herring.

V.1.2 System Hydrodynamic Setting

In Hummock 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, wave over washing of the barrier beach and losses due to evaporation and flow through the beach face into the ocean. On average, the inputs are greater than the losses when the pond is closed off from the ocean and the pond elevation rises.

Typically, two openings per year are made for Hummock Pond by the Town, one each in the spring and the fall seasons. For each opening, a trench is cut across the barrier beach (Cisco Beach). The initial outflow from the pond causes the trench to expand in width as the flow scours sand from the channel. Ideally, the cut would further develop over the course of several tide cycles, and eventually achieve some sort of equilibrium cross-section. Inlets cut for other coastal ponds on the islands can remain open to tidal flushing for periods that span many weeks. Successful opens of this longer duration occur regularly for larger ponds, such as the Great Ponds on the Vineyard. Hummock Pond has a much smaller tidal prism than these larger systems and therefore has less capacity to overcome forces that tend to close a breach (mainly wave driven along-shore sediment transport). Some breaching events of Hummock result in only a lowering of the pond level, and no tidal exchange with the ocean occurs before the new inlet closes. These short or failed breaches only remove the top layer of water from the pond, meaning that there is very little mixing of the nutrient rich water from the pond with the low nutrient 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.

For this study water levels within the pond after two breaches were measured using tide data recorders that measured pond levels every ten minutes. For both recorded breaches (in 2006 and 2012), a successful inlet was not established. The pond level dropped following the breach, but it is evident that the channel did not evolve to the point where tidal flushing occurred.

V.1.3 Pond Management Practices

A record of pond water levels and breachings between 1995 and 2007 was available from the Nantucket Marine Department annual Hummock Pond water quality reports. The record (Table V-1) shows that there are typically two openings made each year, with an average opening duration of 7 days. The maximum number of days that an inlet has remained open is 19 days, while some breaches close after only one day. The annual average number of cumulative days that the pond is open according to the Marine Department records is 16 days.

Table V-1. Annual Hummock Pond openings between 1995 and 2007, Town Marine Department records.

Year	1995	1996	1997	1998	2000	2001	2002	2003	2004	2005	2006	2007
Openings	2	4	2	2	2	2	2	2	2	2	2	2
Cumulative days opens	9	19	24	13	24	18	10	16	12	14	14	17

V.2 HYDRODYNAMIC FIELD DATA COLLECTION AND ANALYSIS

The field data collection portion of this study was performed to characterize the physical properties of Hummock Pond. Bathymetry data were collected throughout the system so that the pond could be accurately represented as a computer hydrodynamic model, and so that flushing rates could be determined for the system. In addition to the bathymetry, tide data were also collected to run the circulation model with real tides, and also to calibrate and verify its performance.

V.2.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the pond were assembled from a 2007 boat-based hydrographic survey. The survey was executed specifically as part of the Massachusetts Estuaries Project analysis.

The hydrographic survey conducted on October 25, 2007 was designed to cover the entire main basin of Hummock Pond and the attached Head of Hummock subembayment. The survey was conducted 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. Land based measurements were conducted in shallow areas where high bathymetric resolution would be beneficial to the model, using the same GPS system.

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to mean sea level (MSL). 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-2.

V.2.2 Tide Data

Tide data records were collected in Hummock Pond during two separate tide gauge deployments. In 2006, Temperature Depth Recorders (TDR) were deployed in the main basin of the system and offshore, and collected data between October and January of the following year. The gauges had been deployed to capture water level fluctuations resulting from the autumn breach of the pond. The other gauge deployment was between October and December of 2012. This deployment period also captured the autumn breach of that year. Though an offshore gauge was deployed in 2012, it was not recovered, and likely buried in the shifting sand offshore. Because of the loss, water levels recorded at the Martha’s Vineyard Coastal Observatory (MVCO) were used the source of offshore data for the second deployment period.

Once the data from each station were downloaded from the instruments, the raw pressure data recorded by the TDRs were corrected for variations in atmospheric pressure. Hourly atmospheric pressure readings were obtained from the meteorological station at Nantucket Memorial Airport (ACK), interpolated to 10-minute intervals, and subtracted from the pressure readings, resulting in variations in water pressure above the instrument. A (constant) water density value of 1025 kg/m^3 was applied to the readings to convert from pressure units (psi) to head units (for example, feet of water above the tide gauge). The result from each gauge is a time series record representing the variations in water surface elevation relative to a known datum. Plots of the water levels following the 2006 and 2012 breaches are shown in Figures V-3 and V-4, respectively. These two plots show that both breach events allowed the pond to drain approximately two feet, though tidal exchange with the ocean did not occur. In both instances, it is evident that storm events followed both breachings within a few days, which caused water levels in the pond to quickly rise to near their pre-breach levels.

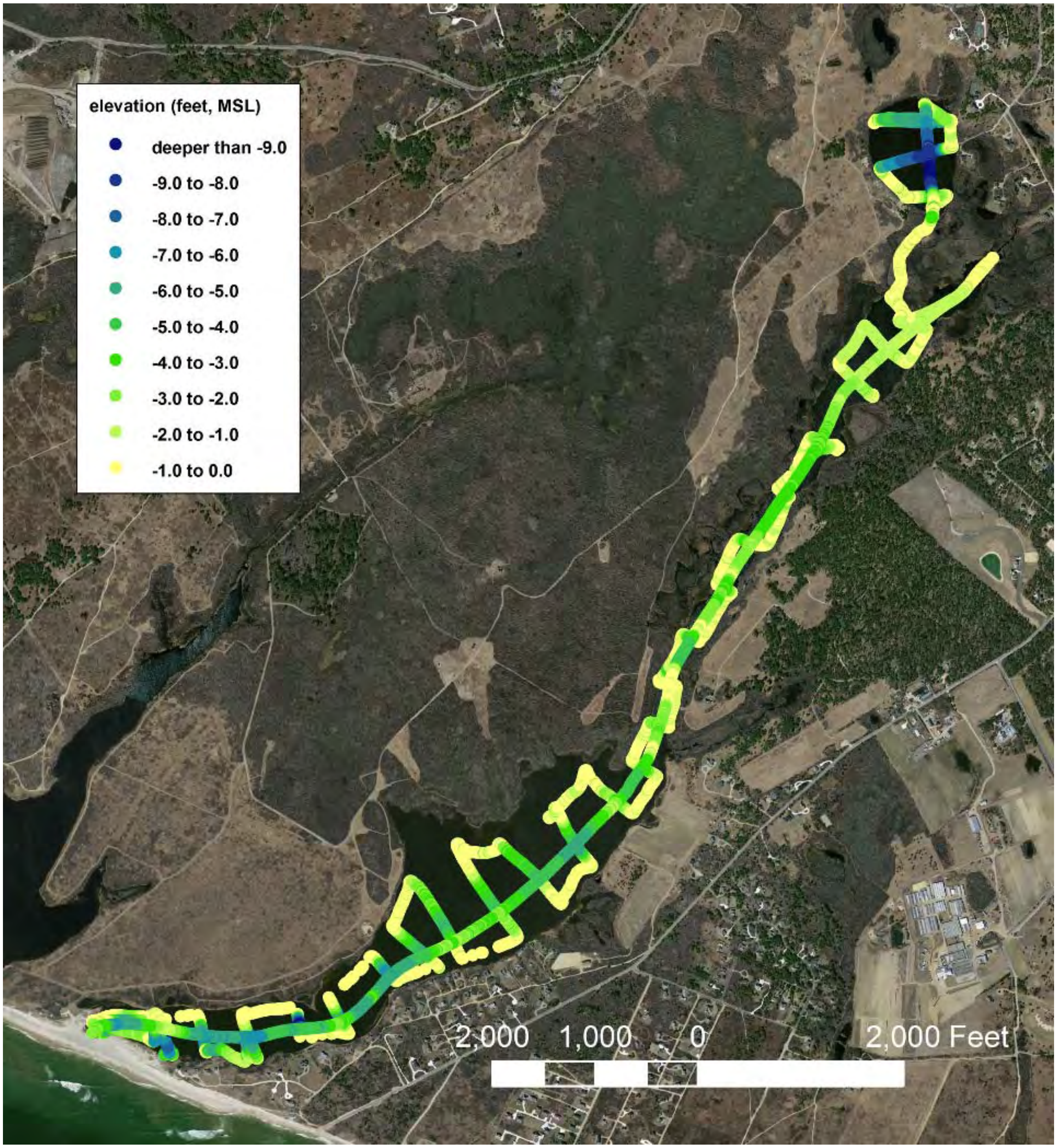

Figure V-2. Bathymetry survey lines (yellow) and tide locations (red) in Hummock Pond.

The standard tide datums were computed for the data recorded offshore of the pond in 2006. These datums are presented in Table V-2. For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data were available; however, these datums still provide a useful comparison of tidal dynamics within the system. The Mean Higher High (MHH) and Mean Lower Low (MLL) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW.

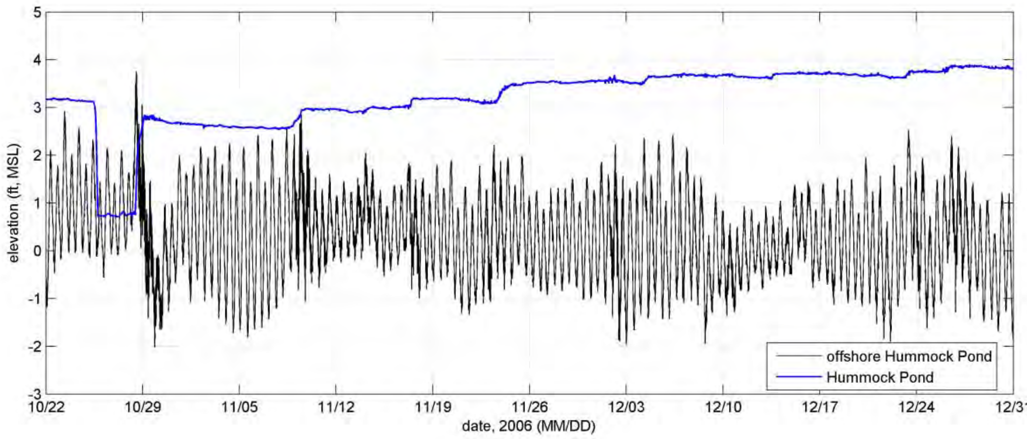

Figure V-3. Observed water levels at the time of the autumn 2006 breach event. The blue line shows water levels in the pond, while tides recorded offshore of the pond are shown by the black line.

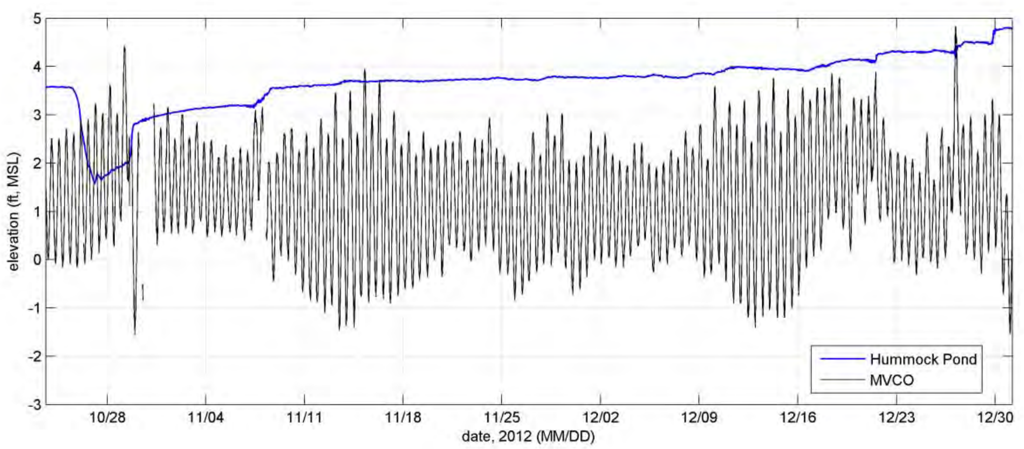

Figure V-4. Observed water levels at the time of the autumn 2012 breach event. The blue line shows water levels in the pond, the black line shows tides recorded at the Martha's Vineyard Coastal Observatory.

Table V-2. Tide datums computed from 92-day records collected offshore Hummock Pond starting October 20, 2006. Datum elevations are given relative to the mean sea level reference of the area.

Tide Datum	Offshore Hummock Pond (feet)
Maximum Tide	3.8
MHHW	1.7
MHW	1.5
MTL	0.3
MLW	-0.9
MLLW	-1.1
Minimum Tide	-2.0
Mean Range	2.4

A harmonic analysis of the offshore tidal time series was also performed to produce tidal amplitude and phase of the major tidal constituents, and provide assessments of hydrodynamic 'efficiency' of the system in terms of tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each system. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The observed astronomical tide is the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-5. The amplitudes and phase of 22 known tidal constituents result from this procedure. Table V-3 presents the amplitudes of seven tidal constituents computed for the offshore station record for the entire time series.

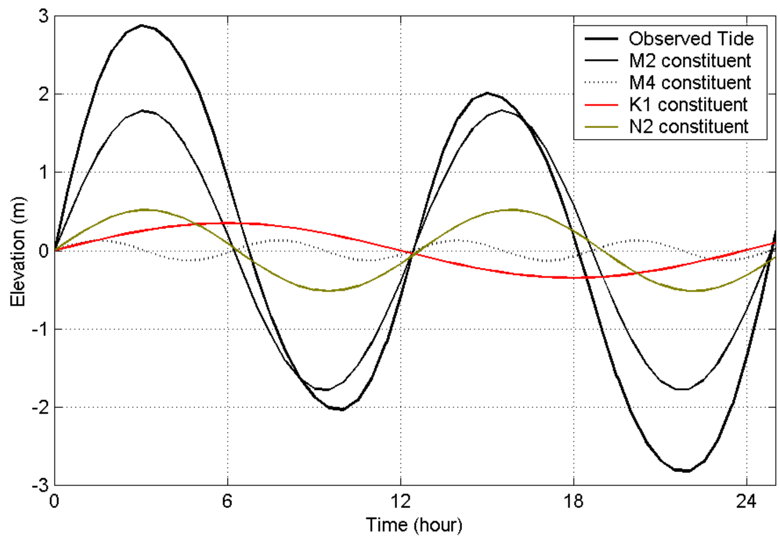

Figure V-5. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-3. Tidal constituents computed for tide station offshore Hummock Pond using the record from October 2006 through January 2007.

	Amplitude (feet)						
Constituent	M_2	M_4	M_6	S_2	N_2	K_1	O_1
Period (hours)	12.42	6.21	4.14	12	12.66	23.93	25.82
Offshore Hummock Pond	0.95	0.11	0.04	0.20	0.23	0.23	0.20

An analysis of the entire offshore record shows that amplitude the M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an offshore amplitude of 0.95 feet. The total range of the M_2 tide is twice the amplitude, or 1.9 feet. The offshore amplitude if the M_2 is approximately two-thirds of the amplitude in Nantucket Harbor. The diurnal tides (once daily), K_1 and O_1, both possess amplitudes of approximately 0.2 feet. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, also contribute to the total tide signal, with amplitudes of approximately 0.2 feet.

In addition to the tidal analysis, the data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. These other processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow.

The results of an analysis to determine the energy distribution (or variance) of the measured water elevation records for the gauge records in Hummock Pond compared to the energy content the astronomical tidal signal (re-created by summing the contributions from the constituents determined by the harmonic analysis) is presented in Table V-4. Subtracting the tidal signal from the original elevation time series results in the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary. Figure V-6 shows the comparison of the measured tide from the tide station offshore of Hummock, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

The results of this harmonic analysis show that for the period of the 2006 deployment, the residual portion (i.e., the non-astronomical signal) of the tide was a large portion of the total observed water level change offshore. In other areas of the Massachusetts coastline, the residual portion of the tide is typically less than 90% of the observed signal, even along the Cape Cod shoreline of Vineyard Sound, which has a smaller mean tide range. The reason the residual is large compared to the astronomical tide at this location is the combination of the small tide range and the unsheltered, open-ocean exposure of this area.

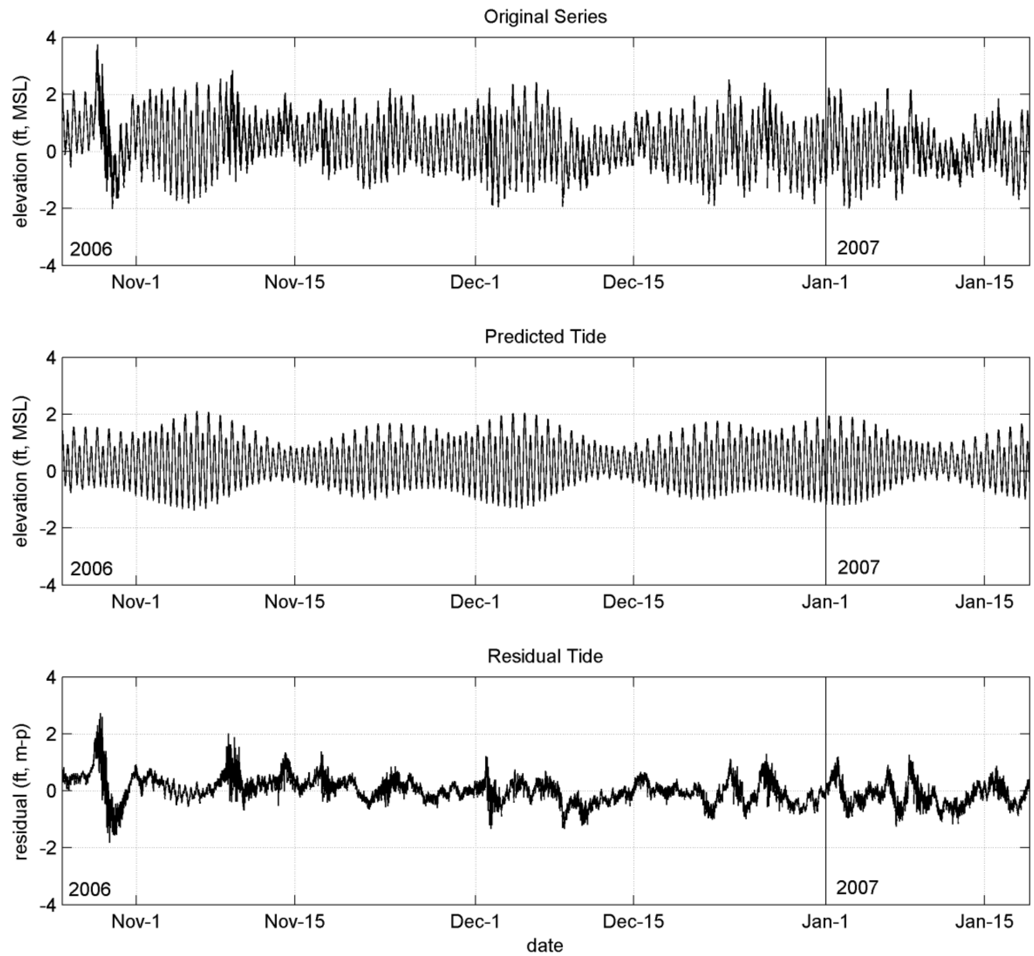

Figure V-6. Measured tide from the gauge station offshore of Hummock Pond, starting in October 2006, with the computed 22 components of astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual water level.

Table V-4. Percentages of Tidal versus Non-Tidal Energy using a 23 constituent analysis for the full tide record recorded offshore of Hummock Pond between October 20, 2006 and January 19, 2007.

TDR Location	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Offshore Hummock	0.745	74	26

V.3 HYDRODYNAMIC MODEL DEVELOPMENT

The formation and final dimensions (width and depth) of the inlet channel through the beach, during the initial draw down of the pond after the inlet is dug by the backhoe, cannot be directly simulated with the RMA suite of models. Therefore, a computer model independent of RMA-2 was used to estimate the inlet channel evolution. The final equilibrated dimensions of the inlet channel determined using this channel model were used in the development of the hydrodynamic numerical model of the system.

V.3.1 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 pond. The channel increases in width and depth during this time and over the first few tides cycles. 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 Hummock Pond.

To assist in the determination of the typical equilibrium cross-section of the Hummock Pond breach, inlets from past breachings were examined using the available historical aerial photographic record. A survey of the aerial record shows that the equilibrated inlet channel width is approximately 55-feet-wide, on average. This average width was used to determine the channel scour depth.

To estimate the channel scour depth, the flow rate through the channel is needed. Using the data from the October 2006 and 2012 breach events, together with the measured surface area of the pond (determined using aerial orthophotos), the average maximum flow rate out of the pond during the breach was determined to be 600 ft^3/sec.

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

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

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 0.4mm was used to represent the sand in this case. Using this equation and stated parameters, an equilibrium channel elevation of -0.2 feet MSL is calculated.

With the initial pond elevation, offshore tides, channel width, and channel depth established, it is possible to compute water levels in the pond through the draw-down period of the pond after the initial breaching of the inlet and the following period when the pond is open to the ocean and tidal. This computed water level time series can then be compared to the actual measured tide in the pond in order to evaluate whether the channel dimensions determined using the USACE equation has produced a useful result that can be used in the development of the RMA-2 hydrodynamic model mesh. To compute a water level time series in the pond, the equation of flow over a broad-crested weir was employed (as described by Hughes, 1999). This equation relates the flow rate through the channel to the channel width and height of water above the channel bottom as

$$Q = 3.0 b H^{3/2}$$

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 3.1 feet MSL (measured just prior to the October 2006 breach) 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. Knowing the surface area of the pond, the change in pond surface elevation is calculated at each time step.

Output generated using the broad-crested weir model is shown in Figure V-7. The simulated breach is run for 20 days, which is longer than breaches of Hummock Pond have lasted based on the historical record. These results are useful to demonstrate the likely range of tidal conditions that would be possible in the pond, through the bi-monthly spring-to-neap tide cycle. The maximum tide range is approximately one foot during the periods of offshore spring tides. During neap tides the tide range is almost zero. The actual tidal conditions in the pond (like those recorded in 2006 and 2012) depend most importantly on the success of the opening. Particularly if the action of waves is great enough to overcome the scouring action of tides through the breach channel, causing a quick closure of the inlet before tidal exchange can occur between the pond and the ocean.

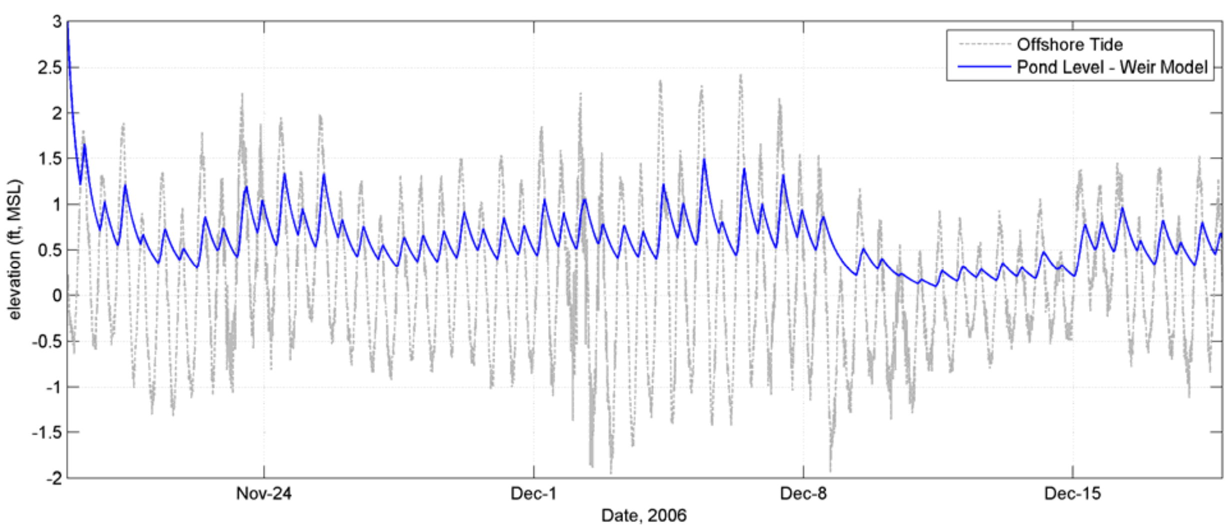

Figure V-7. A comparison of the broad-crested weir model results with the recorded pond elevations during a simulated breach of Hummock Pond that is open for one month. This simulation show the likely range of possible tides in the pond after a breaching.

V.3.2 RMA-2 Model Theory

Applied Coastal utilized a state-of-the-art computer model to evaluate tidal flushing during periods when Hummock Pond is open to the Atlantic Ocean. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2 for numerous flushing studies on Cape Cod, including similarly breached ponds on Nantucket and Martha's Vineyard (Sesechacha, 2006; Edgartown Great Pond, 2007; and Tisbury Great Pond, 2012)

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 prototype 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, 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.3.3 Model Setup

There are three main steps required to implement RMA-2:

- Grid generation
- Boundary condition specification
- Calibration

The extent of each finite element grid was generated using 2009 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of the Hummock Pond grid based on the available 2006 tide data record from offshore of the Pond. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several model calibration simulations for the system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.3.1 Grid generation

The grid generation process was aided by the use of the SMS package. Digital aerial orthophotos (2009) and the 2007 bathymetry survey data were imported to SMS and a finite element grid was generated to represent the estuary. The aerial photographs were used to determine the land boundary of the system, as well as to determine the surface coverage of salt marsh. The bathymetry data were interpolated to the developed finite element mesh of the system. The completed grid consists of 5162 nodes, which describe 1905 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth within the pond is -8.9ft (MSL). The bathymetry of the completed model grid mesh of the Hummock Pond system is shown in Figure V-8. As described previously in this section (V.4.1), the inlet width and depth used in the model are based on the available aerial photographic record and the results of the USACE weir model computations. The final grid mesh is shown in Figure V-9.

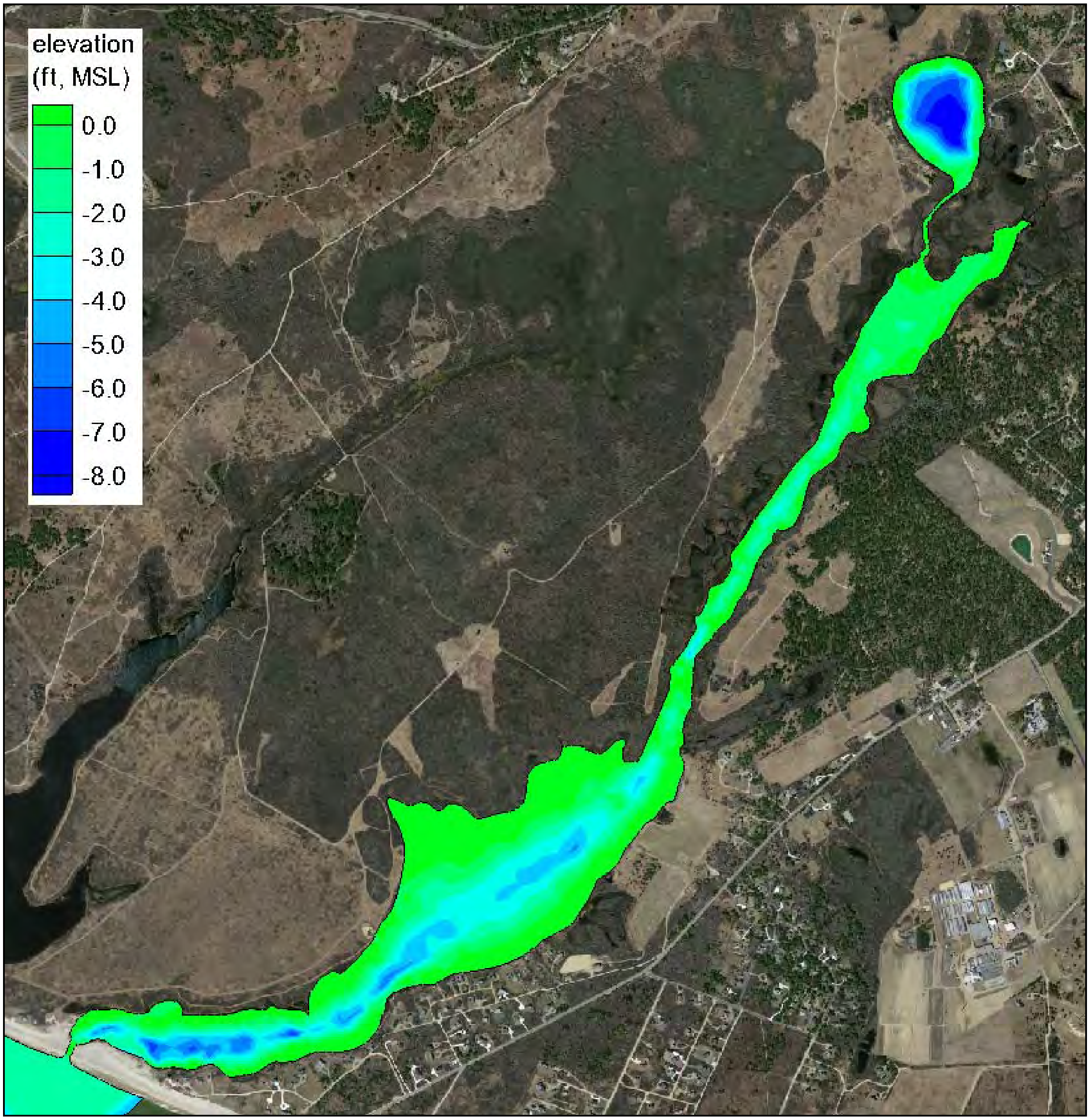

Figure V-8. Bathymetry data interpolated to the finite element mesh used with the RMA-2 hydrodynamic model. Contours represent the bottom elevation relative to North American Vertical Datum 1988. The primary data sources used to develop the grid mesh are the February 2012 surveys of the system.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Hummock Pond. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Grid resolution is generally governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution is employed where complex flow patterns are expected, generally near the inlet. Appropriate implementation of wider node spacing and larger elements reduces computer run time with no sacrifice of accuracy.

V.3.3.2 Boundary condition specification

Three types of boundary conditions were employed for the RMA-2 model of Hummock Pond system: 1) "slip" boundaries, 2) tidal elevation boundaries, and 3) constant flow input boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. A tidal boundary condition was specified at the inlet from the Atlantic Ocean. TDR measurements provided the required data. The rise and fall of the tide in the ocean is the primary driving force for estuarine circulation in this system. Dynamic (time-varying) model simulations specified a new water surface elevation at the open boundary of the Hummock Pond grid every model time step. Runs of the pond model used a 10-minute time step, which the same as the 10-minute sampling rate of the measured tide data. Details concerning the constant flow input boundary conditions included in the hydro model are discussed in Chapter VI.

V.3.3.3 Calibration

After developing the finite element grid, and specifying boundary conditions, the model for Hummock Pond was corroborated using the results of the breach model developed in section V.4.1. The complete model simulation covers a 20-day period from the point when the pond is breached. Computed water levels in the pond were then compared to the output of the breach model to verify that the two methods produced similar results.

Corroboration of the hydrodynamic model required a close match between the modeled and measured tides from stations inside the system (i.e., from the TDR deployments). Initially, the model was calibrated to obtain visual agreement between modeled and measured tides. Once visual agreement was achieved, a calibration of the model was done based on dominant tidal constituents as discussed in Section V.3.2. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents.

The finished model was used to analyze existing detailed flow patterns and compute residence times. The flushing analysis is based on the entire tidal record. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire 20-day simulation. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events.

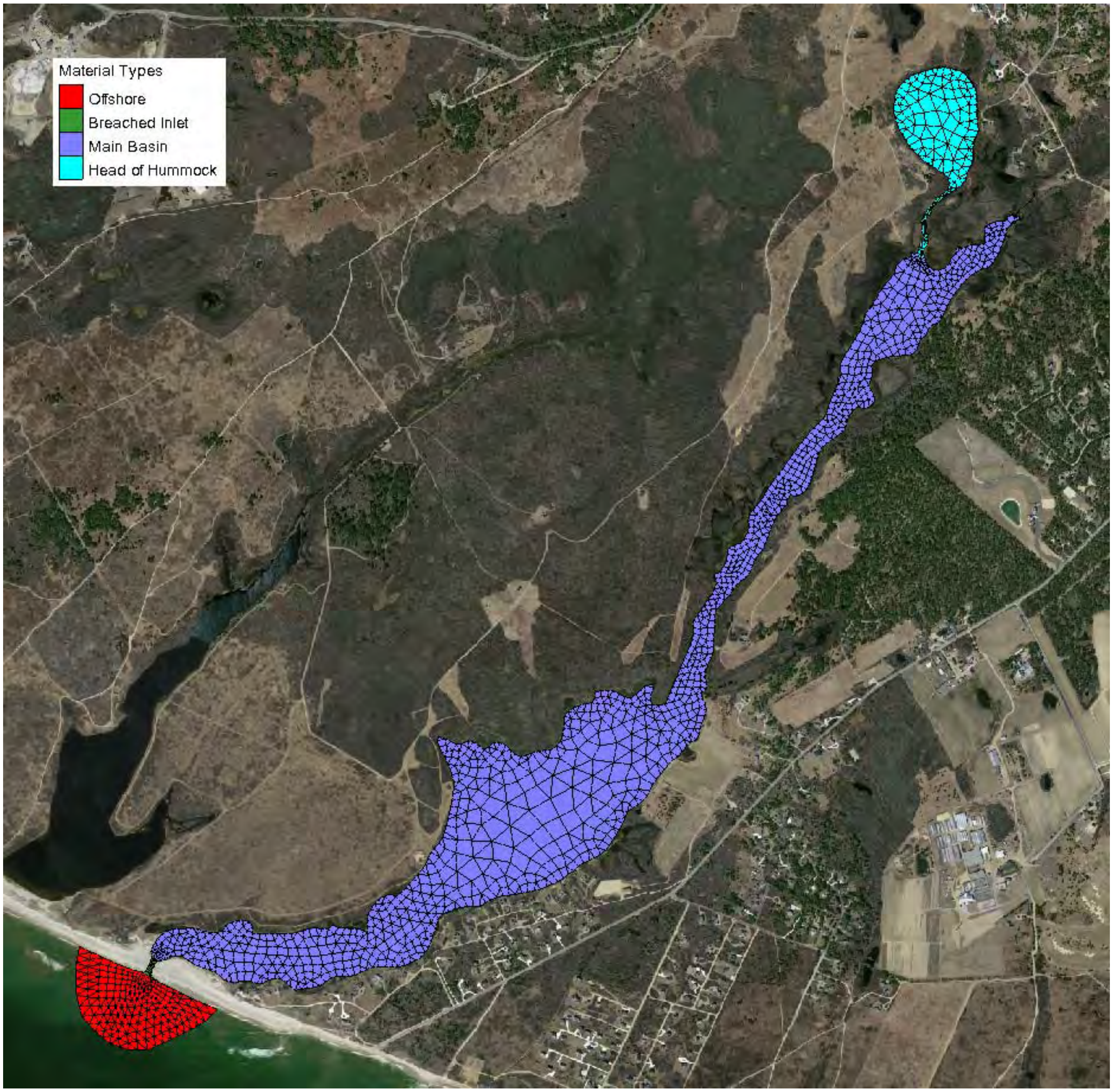

Figure V-9. Plot of hydrodynamic model grid mesh for Hummock Pond. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

V.3.3.3.a Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.02 and 0.025 were specified for all element material types. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels and marsh plains with higher friction (Henderson, 1966).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning's coefficients were matched to bottom type. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based on ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992). Values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-5 for the different regions of the pond specified by the different grid material types of the numerical grid (Figure V-9).

V.3.3.3.b Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 5 and 50 lb-sec/ft^2 (Table V-5).

V.3.3.3.c Marsh porosity processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh areas included in the model of Hummock Pond. Cyclically wet/dry areas of the marsh will tend to store waters as the tide begins to ebb and then slowly release water as the water level drops within the creeks and channels. This store-and-release characteristic of these marsh regions was partially responsible for the distortion of the tidal signal and the elongation of the ebb phase of the tide. On the flood phase, water rises within the channels and creeks initially until water surface elevation reaches the marsh plain, when at this point the water level remains nearly constant as water 'fans' out over the marsh surface. The rapid flooding of the marsh surface corresponds to a flattening out of the tide curve approaching high water. Marsh porosity is a feature of the RMA-2 model that permits the modeling of hydrodynamics in marshes. This model feature essentially simulates the store-and-release capability of the marsh plain by allowing grid elements to transition gradually between wet and dry states. This technique allows RMA-2 to change the ability of an element to hold water, like squeezing a sponge.

Table V-5. Manning's Roughness and eddy viscosity coefficients used in simulations of Hummock Pond. These embayment delineations correspond to the material type areas shown in Figure V-10.

System Embayment	bottom friction	eddy viscosity lb-sec/ft^2
Offshore	0.025	30
Breach Inlet	0.025	50
Hummock Pond Main Basin	0.025	20
Head of Hummock	0.025	20

V.3.3.3.d Comparison of modeled tides and measured tide data

A best-fit of model output for the measured data was achieved using the aforementioned values for friction and turbulent exchange. Figure V-10 shows the comparison between tides calculated using the simple breach model and the output of the two-dimensional hydrodynamic model. The R^2 correlation between the two simulation is 0.89, with an RMS error of 0.07 feet. This indicates that the breach channel cross-sectional dimensions are a realistic representation of a fully developed inlet.

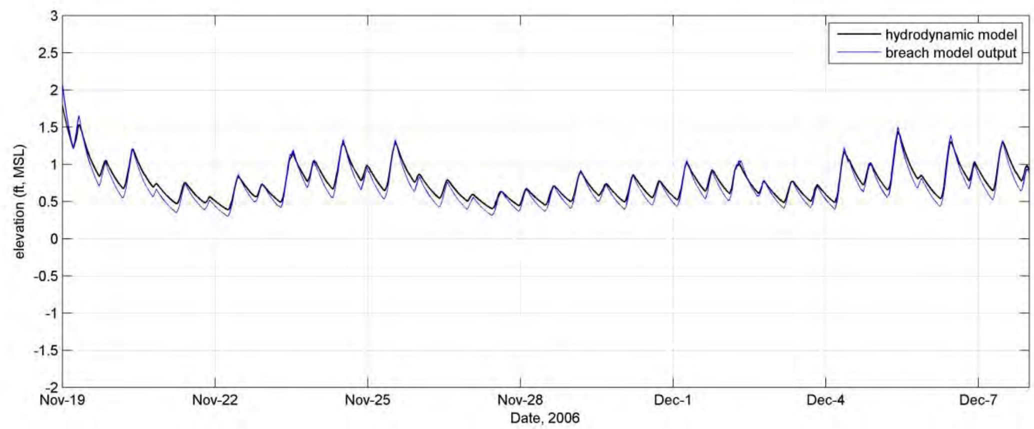

Figure V-10. Comparison of results calculated using the breach model (section V.4.1) and the hydrodynamic model of Hummock Pond. The R2 correlation between the two models for the time period shown in the plot is 0.89, with a RMS error of 0.07 feet.

As another example, from the completed Hummock Pond model, the total flow rate of water flowing through the breached inlet channel can be computed using the hydrodynamic model. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-11. After the initial breaching, the maximum flood flow rates reach 500 ft^3/sec across the breach during spring tides.

V.3.4 Flushing Characteristics

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through the inlet, the primary mechanism controlling estuarine water quality within the modeled Hummock Pond system is tidal exchange. A rising tide offshore creates a slope in water surface from the ocean into the upper-most reaches of the modeled system. Consequently, water flows into (floods) the system. Similarly, the estuary drains into the open waters of the ocean on an ebbing tide. This exchange of water between the system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of the harbor system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

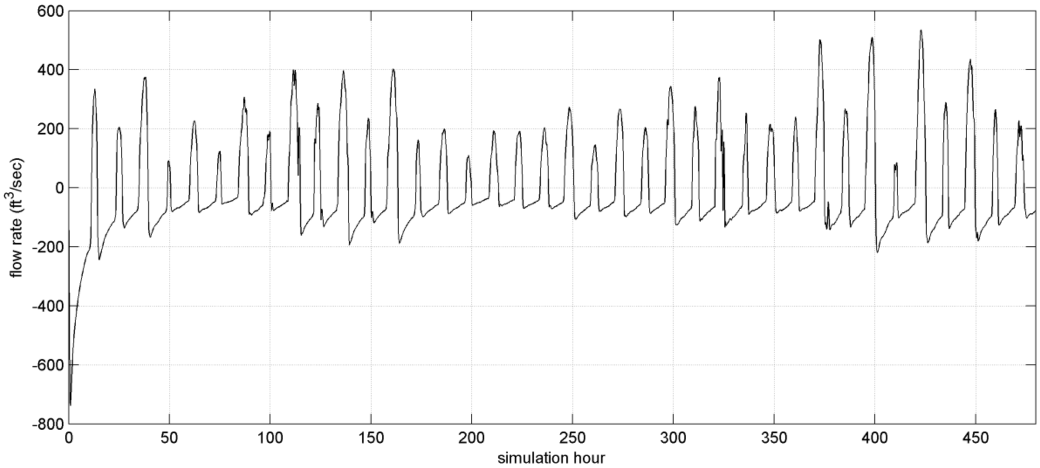

Figure V-11. Time variation of computed flow rates for the modeled Hummock Pond breach. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flow indicated flooding tide flows into the Pond, while negative flow indicates ebbing tide flows discharging from the pond.

Flushing rate, or residence time, is defined as the average time required for a parcel of water to migrate out of an estuary from points within the system. For this study, **system residence times** were computed as the average time required for a water parcel to migrate from a point within the each embayment to the entrance of the system. 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 (entire) system at mean tide level, P equals the tidal prism (or volume entering the system through a single tidal cycle), and t_{cycle} the period of the tidal cycle, typically 12.42 hours (or 0.52 days). To compute system residence time for a sub-embayment, the tidal prism of the sub-embayment replaces the total system tidal prism value in the above equation.

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using Head of Hummock as an example, the **system residence time** is the average time required for water to migrate from this upper-most area of the system, out through the main body of Hummock Pond, and into the ocean, where the **local residence time** is the average time required for water to migrate from Head of Hummock and into the main basin of Hummock Pond (not all the way to the ocean). Local residence times for each sub-embayment are computed as:

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

where T_{local} denotes the residence time for the local sub-embayment, V_{local} represents the volume of the sub-embayment at mean tide level, P equals the tidal prism (or volume entering the local sub-embayment through a single tidal cycle), and t_{cycle} the period of the tidal cycle (again, 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. For Hummock Pond this approach is applicable during periods when a breach is open to the ocean, since it assumes the main system has relatively lower quality water relative to offshore waters.

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. It is impossible to evaluate an estuary's health based solely on flushing rates. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the estuary 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 estuary is of poor quality. Advanced understanding of water quality is obtained from the calibrated hydrodynamic model in the following section of this report (Section VI) by extending the model to include pollutant/nutrient dispersion. The water quality model provides an additional valuable tool to evaluate the complex mechanisms governing estuarine water quality in the system.

Since the calibrated RMA-2 model simulated accurate two-dimensional hydrodynamics in the system, model results were used to compute residence times. Residence times were computed for the entire estuary, as well the four subdivisions of the system. In addition, **system** and **local residence times** were computed to indicate the range of conditions possible for the system.

Residence times were calculated as the volume of water (based on the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Model divisions used to define the system sub-embayments simply include: 1) the entire Hummock Pond system and 2) Head of Hummock. These two system divisions follow the model material type areas designated in Figure V-9. Sub-embayment mean volumes and tidal prisms are presented in Table V-6.

Table V-6. Embayment mean volumes and average tidal prism for the Hummock Pond system.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Hummock Pond System	21,245,100	2,600,300
Head of Hummock	3,603,900	266,100

Residence times were averaged for the tidal cycles comprising a representative 20 day period (48 tide cycles) using the finished model and tidal boundary condition data from the station offshore of the pond, and are listed in Table V-7. These flushing rates assume that a successful breach is established and remains open for the full 20 days of the model run. This is not representative of typical breach conditions, but provides a good estimate of the best flushing conditions possible for the pond. The modeled period used to do these calculations excludes the initial system draining time corresponding with the creation of the inlet. The RMA-2 model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume. Since the period used to compute the flushing rates of the system represent average tidal conditions when the inlet is open, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments after a successful breach.

Table V-7. Computed System and Local residence times for the whole of the Hummock Pond estuarine system and for the Head of Hummock sub-embayment.

Embayment	System Residence Time (days)	Local Residence Time (days)
Hummock Pond System	4.2	4.2
Head of Hummock	41.3	7.0

A flushing time of 4.2 days for the entire estuary shows that on average, water is resident in the system for more than four days. This modest residence time provides some confidence that the temporary channel could allow enough exchange to significantly improve water quality during a typical breach event. Head of Hummock has a large system residence time that is greater than 41 days, which indicates that the flushing ability of the pond is greatly dependent on water quality in the main basin of the pond. The long local flushing residence time for Head of Hummock is equal to the average recorded breach opening duration, which indicates that typical breach conditions would not have a duration that is long enough to be completely restorative to habitat in this upper-most region of the system.

Based on our knowledge of estuarine processes, we estimate that the combined errors associated with the method applied to compute residence times are within 10% to 15% of “true” residence times, for the Hummock Pond system, with the establishment of a successful breach. Possible errors in computed residence times can be linked to: the bathymetry information, simplifications employed to calculate residence time and the assumed stability of the inlet. In this study, the most significant errors associated with the bathymetry data result from the process of interpolating the data to the finite element mesh, which was the basis for all the flushing volumes used in the analysis. In addition, limited topographic measurements were available in some of the smaller sub-embayments of the system.

Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. However, water exiting a small sub-embayment on a relatively calm day may not completely mix with estuarine waters. In this case, the “strong littoral drift” assumption would lead to an under-prediction of residence time. Since littoral drift along the southern shoreline of Martha’s Vineyard typically is strong because of the effects of the local winds, waves, and tidal induced mixing, the “strong littoral drift” assumption only will cause minor errors in residence time calculations.

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 Hummock Pond. This modified approach has been applied to other estuary systems that are periodically breached, like Edgartown and Tisbury Great Ponds, both located on the south shore of the Vineyard, and Sesechacha Pond, on the eastern shore of Nantucket.

This system differs from most other systems modeled as part of the MEP because it does not have an inlet that is open at all times to the ocean. Water quality in the Pond is managed presently by periodically opening an inlet to the ocean. For past breaches, the length of time that the inlet remains open after it is breached varies between 1 and 19 days, based on reported observations of the Nantucket Marine Department for openings made from 1995 through 2007. On average, the pond is open 16 days total per year, which means it is closed off from the ocean 96% of the time. The reported days open for a breaching event does not indicate the number of days during which tidal exchange occurs with the ocean. The breach that is cut does not always develop into a stable inlet that allows tidal flows in and out of the pond, even for short periods. Past breachings often only result in a lowering of the pond water levels, which does nothing to reduce TN concentrations in the pond.

Because Hummock Pond is actively managed by periodically breaching an inlet, 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 an inlet is open, the RMA-4 model was used to model water quality constituent dispersion throughout the pond. During the long periods when the breach is closed, a separate modified version of the RMA-4 model was utilized where no open ocean tidal boundary is included. As used together in this analysis, these two models simulated conditions in the pond throughout the critical summer months, and provided a method of investigating alternatives for managing 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 Hummock 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 using tide data record measured offshore of Katama Beach, at the Martha's Vineyard Coastal Observatory (MVCO). These tide data were used as a boundary condition to force the RMA-2 model of Hummock Pond.

VI.1.2 Nitrogen Loading to the Embayments

Three primary nitrogen loads to Hummock Pond are included in this modeling study: external loads from the watersheds, nitrogen load from direct rainfall on the embayment surface, and internal loads from the sediments. In addition to these three nitrogen loads to the pond, the Atlantic Ocean is a background source of nitrogen that is important to include in the model when simulating periods when the pond inlet is open and flushing. 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 Hummock 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 stations 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. For Hummock Pond, a maximum of 2 years of salinity and TN measurements are available from the years 2010 and 2012.

Table VI-1. Measured nitrogen concentrations and salinities for Hummock Pond. "Data mean" values are calculated as the average of the separate yearly means. TN data represented in this table were collected in 2010 and 2012. The offshore Atlantic Ocean data (offshore Pleasant Bay Inlet) are from the summer of 2005.

Sampling Station Location	Station ID	Years of Data	total nitrogen			salinity		
			data mean (mg/L)	s.d. all data (mg/L)	N	data mean (ppt)	s.d. all data (ppt)	N
Lower-most Hummock	HUM-1	2	0.648	0.140	17	6.9	1.4	19
Lower Hummock	HUM-2	2	0.737	0.193	8	7.1	1.6	8
Lower Hummock	HUM-3	2	0.715	0.184	18	6.7	1.3	20
Middle Hummock	HUM-5	2	0.813	0.174	24	6.0	1.4	25
Uppermost Hummock	HUM-8	2	0.985	0.183	12	5.2	1.4	13
Head of Hummock	HUM-7	2	1.630	0.802	18	4.3	1.2	18
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 Hummock 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 Hummock Pond. In such simple systems it is an easy task to compute water recharge and rainfall rates based on the observed salinity record.

The Hummock 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 early summer 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 also simulated using the RMA-4 and also includes fresh water inputs and constituent mass flux into the Pond (which is 0 for the salinity simulation) throughout the simulation period.

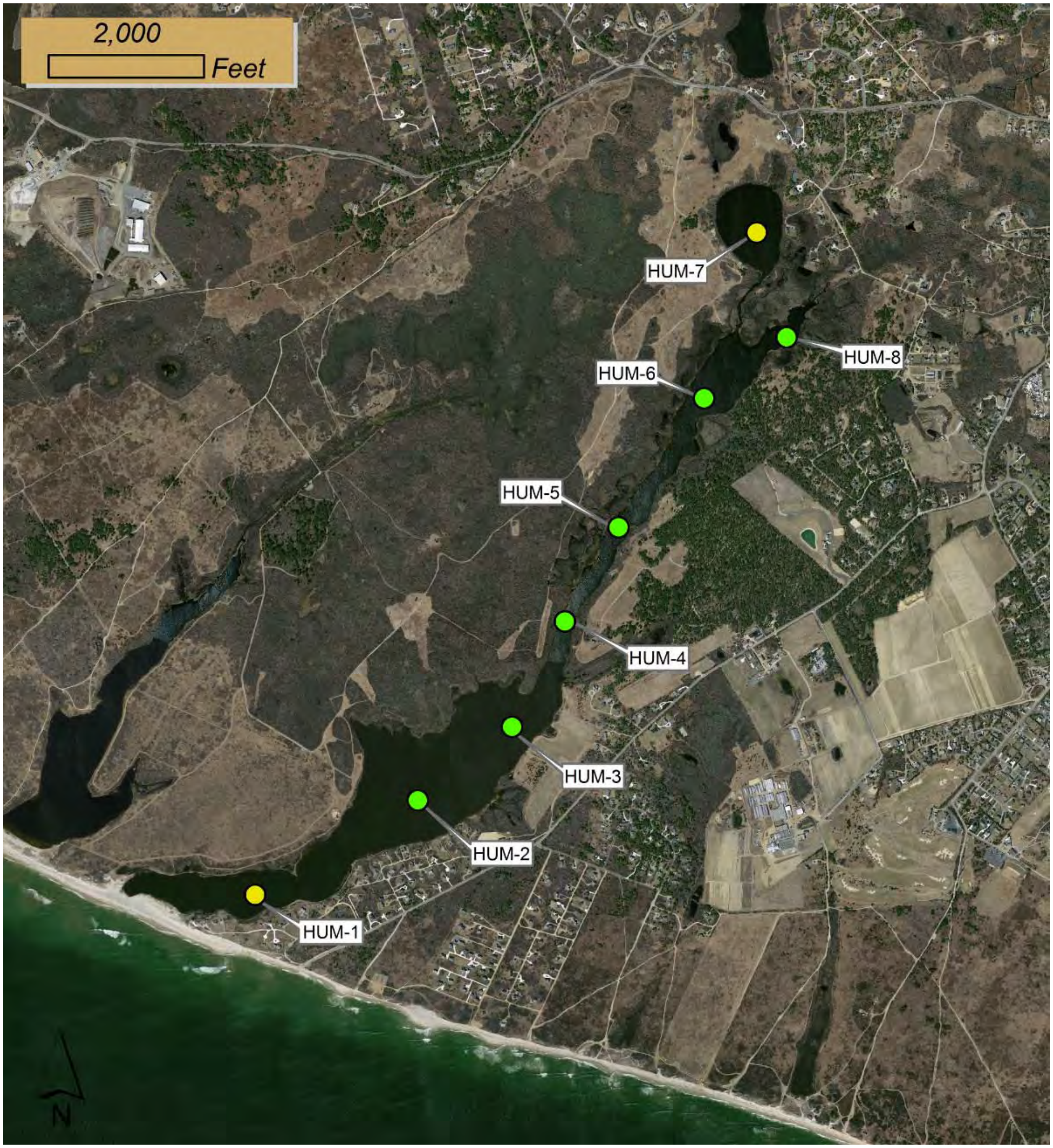

Figure VI-1. USGS topographic map showing monitoring station locations in Hummock Pond that were designated by the Nantucket Marine Department.

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 watershed loading analysis presented in Chapter IV of this report, 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

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of water quality constituent dispersion in Hummock Pond during the periods when it is open and also closed to the ocean and tidal flushing. 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), and including other periodically breached coastal ponds like Sesachacha Pond (Howes *et al*., 2006) on the eastern shoreline of Nantucket.

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. The water quality model evaluates model parameters at every element in the model grid at the same time intervals used in the hydrodynamic simulation (every 10 minutes for the tidal simulation and every hour for the model that represents the long time periods when the pond inlet is closed. For this application, the RMA-4 model was used to predict time varying salinity and total nitrogen concentrations throughout Hummock Pond over the course of a four-day long opening and a subsequent 60-day closed period. Marine Department data shows that past breaches are open for an average of 6 days, though there is evidence (from tide data taken from the pond) that this data may not represent the time that the pond is actually flushing openly with the ocean. The four-day period used for this analysis is considered to be a better approximation of the typical length of time that the pond would be tidally flushing under optimum breach conditions.

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, direct atmospheric deposition and benthic flux loads for the whole Pond were evenly distributed across the cells that make up the RMA computational grid.

The loadings used to model present conditions in Hummock 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. Sediments in the northern basin of the Pond tend to have negative fluxes, which indicates that they are a nitrogen sink. The N production of the bottom sediment in other 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 for the simulation of periods when the inlet is open. 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. Present conditions sub-embayment and surface water loads used for total nitrogen modeling of Hummock Pond, 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)
Hummock Pond main basin	11.195	1.918	0.196
Head of Hummock	1.682	0.208	1.321
Total	12.877	2.126	1.517

VI.2.3 Development of Present Conditions Model

To simulate present water quality conditions in Hummock Pond, separate RMA-4 models were developed to represent conditions in the Pond when the inlet is open and the pond is tidally flushing and also for periods when the inlet is closed.

For time periods when the pond was closed off from the ocean, a RMA model that has no open ocean boundary condition was developed and calibrated. This model requires an initial salinity and pond water level, as well as a fresh water flux into the pond (groundwater and surface water discharge) and pond water discharge through the barrier beach. The closed pond model was calibrated using data from summer 2012, which is a period where good-quality contemporaneous TN, salinity, and pond elevation data exist. The initial salinity (8.7 ppt) was measured on June 27. The initial Pond elevation was set at 0.8 feet MSL based on tide gauge records from past breachings in 2007 and 2012. The net freshwater input (groundwater and streams) to the model is 5.5 ft^3/sec.

The model was calibrated by only changing the values of the diffusion coefficient applied to the different areas of the modeled domain. Diffusion coefficient values determined during the model calibration process are listed in Table V-3 for the sub-divisions of the Pond. A plot of model output versus measured salinities in the pond (HUM-3) used for the calibration is presented in Figure VI-2, for the start and end of the 58-day simulation. The modeled and measured data show good agreement, with a RMS error of 0.9 ppt. A contour plot of salinity in the Pond at the beginning of the simulation using the "closed" model is presented in Figure VI-3.

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for the Hummock Pond estuary system.

Embayment Division	E m^2/sec
Hummock Pond main basin	14.0
Head of Hummock Pond	14.0
Inlet	5.0

By opening the calibrated salinity model to ocean tides, the behavior of the system when it is tidally flushing can be simulated. Figure VI-4 shows traces of salinity at monitoring station HUM-3 for initial conditions (3.8 ppt). This simulation was run with the same open ocean tidal boundary condition developed from measured MVCO tide data, as discussed in Chapter V. The plot of salinities in the main basin of the Pond show that after 7 days of tidal flushing, salinities continue to increase, but at a slower rate than when the breach is first opened. This indicates that with optimal tidal flushing conditions (i.e., with the formation of a stable inlet), the pond can be well flushed after about 1 week from most any starting condition in the Pond. The actual stability (as effected by storms and waves) of an inlet cut would, of course, control the rate of water quality improvements.

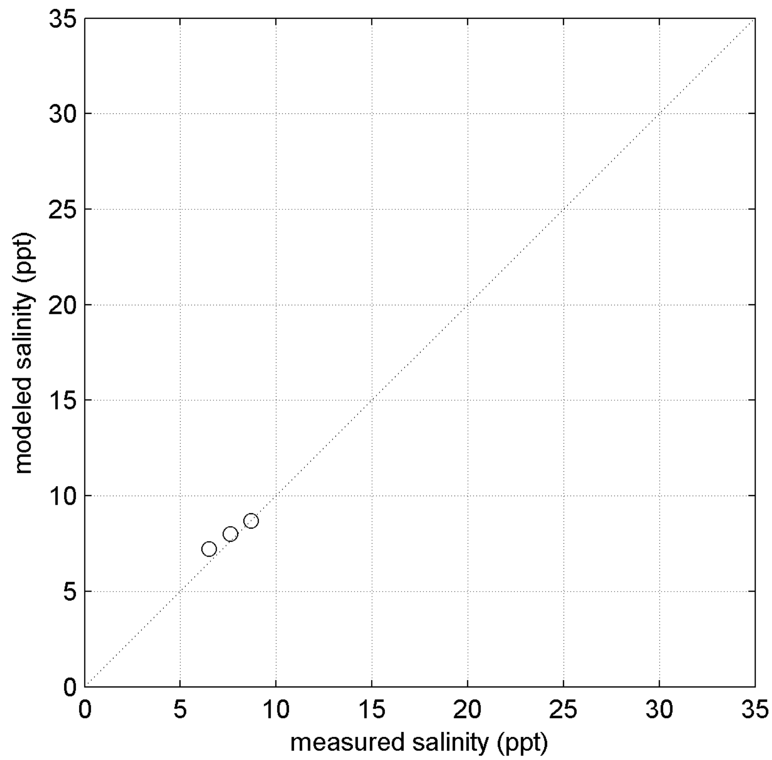

Figure VI-2. Model salinity target values are plotted against measured data, together with the unity line, for the simulation period from June 27 through August 24, 2012. RMS error for this model verification run is 0.9 ppt.

VI.2.4 Total Nitrogen Model Development

With the diffusion coefficients determined from the salinity model calibration, the TN model of Hummock Pond was developed using the watershed and atmospheric loads presented in Table V-2. Benthic loads were computed based on the spatial distribution of the cores sampled for this study. In the model calibration period between June 27 and August 24, 2012 TN concentrations rose from 0.67 mg/L to 0.98 mg/L in the main basin of the pond. Initial TN concentrations at the start of the simulation were set in the pond using the measured TN data from August 3. This established the gradient of TN concentrations across the pond that existed at the beginning of the simulation period.

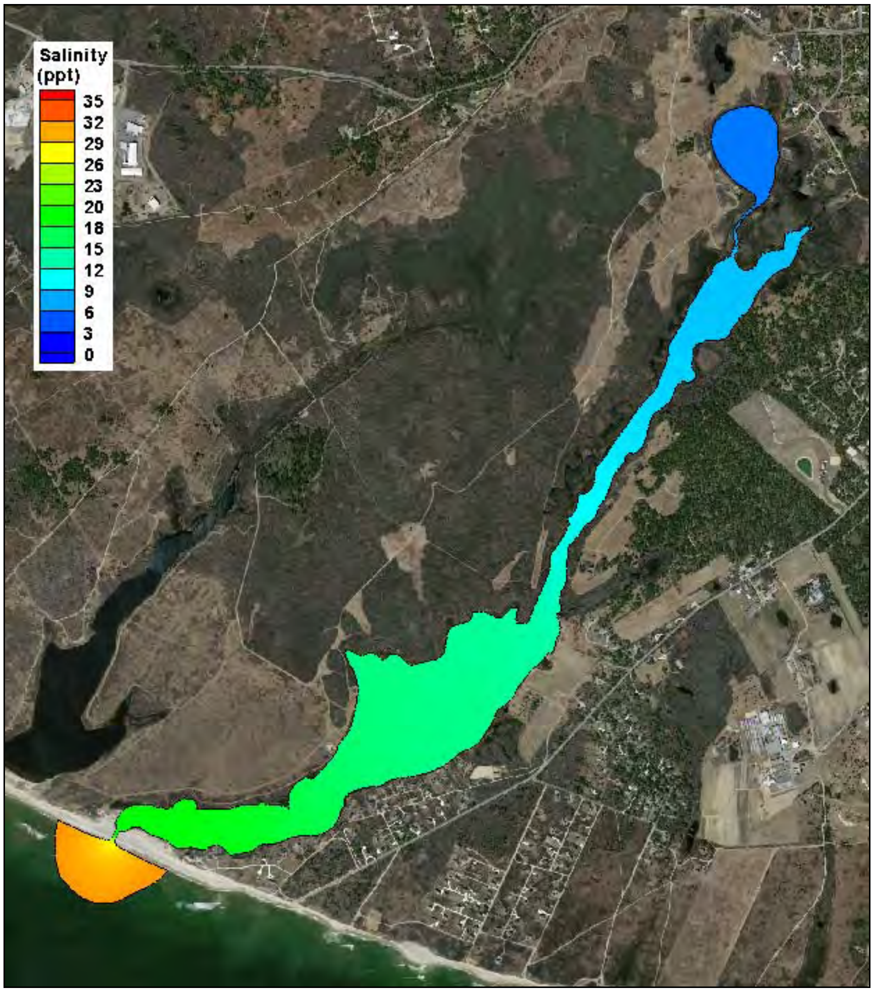

Figure VI-3. Plot of salinity contours in Hummock Pond and Black Point Pond at the end of the modeled August 2006 calibration period.

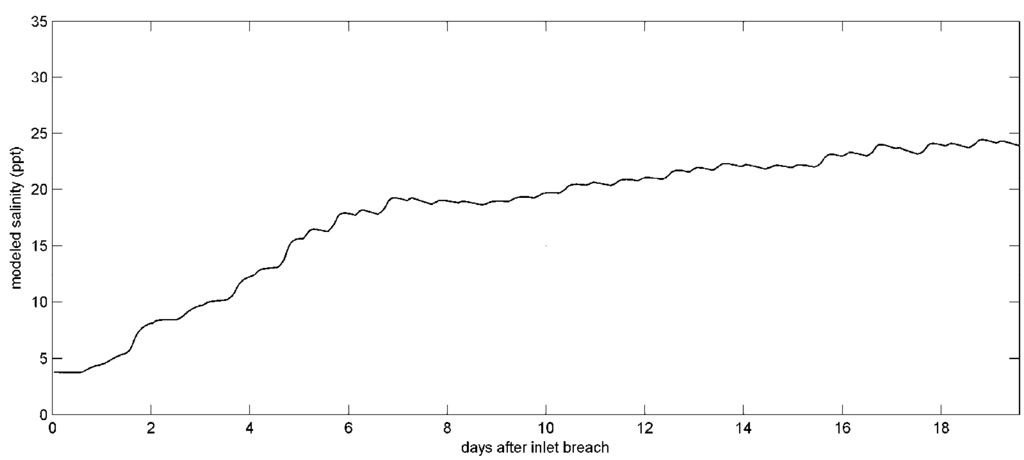

Figure VI-4. RMA-4 model output for Hummock Pond showing how pond salinities vary with the number of days open for a breached inlet. Model output is taken at monitoring station HUM-3. Model results also assume a fully open breach for the complete simulation period.

Using the initial TN concentrations gradient, nitrogen sources from Table VI-2, and diffusion coefficients from Table VI-3, the model is able to accurately simulate this rise in the main basin and in Town Cove. In the model TN rises from 0.67 mg/L to 0.92 mg/L at station HUM-3 in the main basin. Model output plotted versus measured data presented in Figure VI-5 show that the TN model represents well the rise of TN concentrations in the Pond during the simulation period, with a RMS error of 0.06 mg/L and an R^2 of 0.71. Contours of TN concentrations across the Pond at the beginning of the closed pond simulation are presented in Figure VI-6.

Similar to the salinity model, the calibrated model was opened to tidal flushing to simulate how TN concentrations change when the system is breached (Figure VI-7). The results are for an initial TN concentration of 0.6 mg/L. Similar to the salinity model results, after day 7 of the model run TN concentrations are essentially the same for the remainder of the modeled time period. This corroborates the results of the salinity model, which suggest that 7 days is the minimum period of open ocean exchange required to bring the pond to a state of tidal equilibrium.

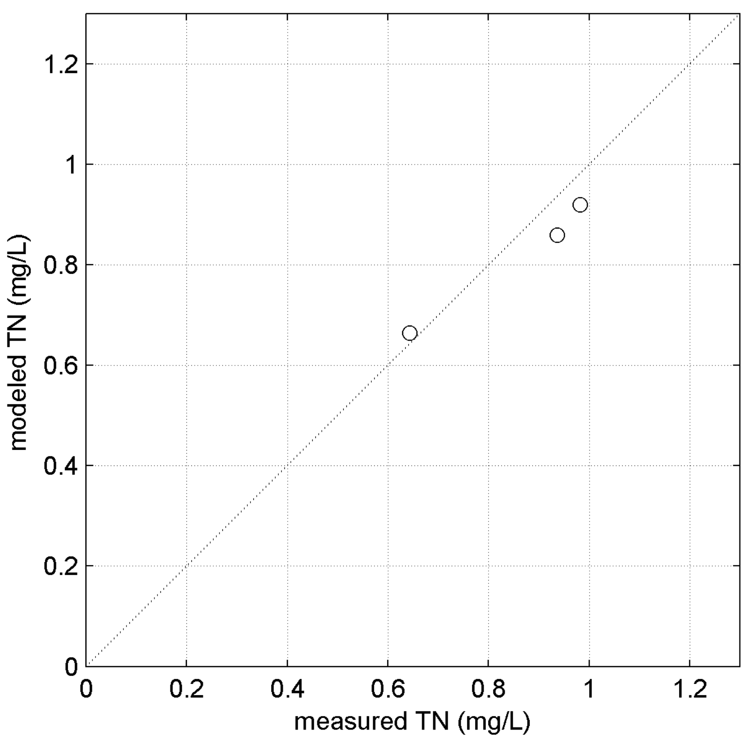

Figure VI-5. Model TN target values are plotted against measured concentrations, together with the unity line, for the simulation period from June 27 through August 24, 2012. RMS error for this model verification run is 0.058 mg/L and the R^2 correlation coefficient is 0.71.

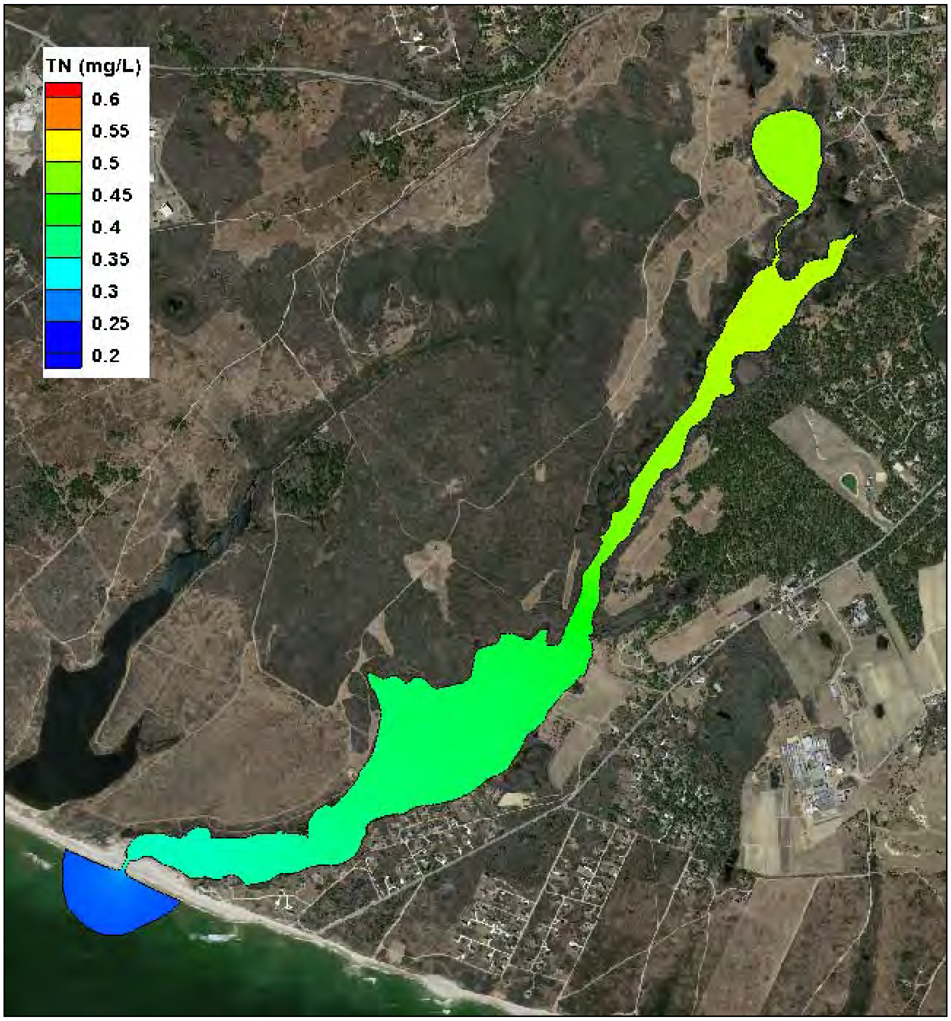

Figure VI-6. Plot of TN contours in Hummock Pond and Black Point Pond at the end of the modeled August 2006 calibration period.

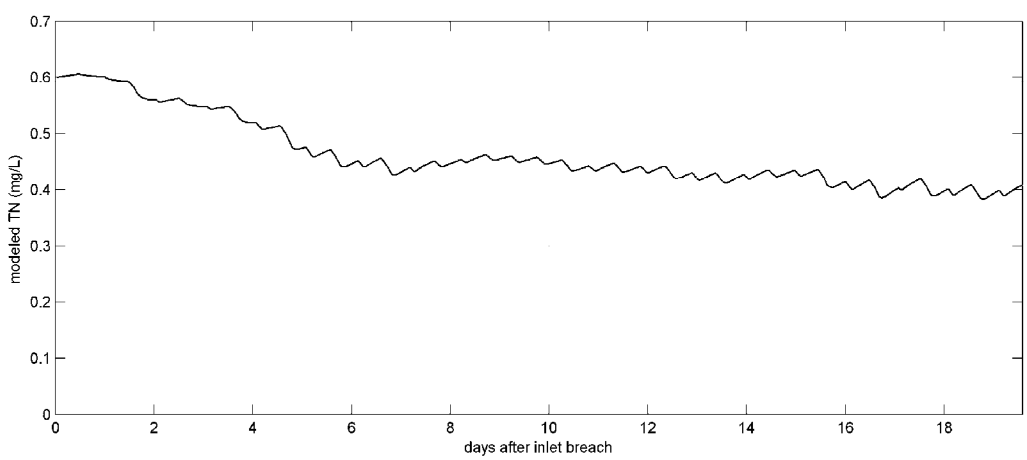

Figure VI-7. RMA-4 model output for Hummock Pond showing how pond TN concentrations vary as a function of initial salinity concentration (here for 10, 15 and 20 ppt) and number of days open for the breach. Model output is taken at monitoring station HUM-3. Model results also assume a fully open breach for the complete simulation period.

VI.2.5 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations in Hummock 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. 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. The changes in watershed loads compared to present conditions are presented in Table VI-4.

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present (2003), present 2007, build-out, and no-anthropogenic ("no-load") loading scenarios of Hummock 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
Hummock Pond main basin	11.195	14.258	*+27.4%*	0.693	*-93.8%*
Head of Hummock	1.682	1.888	*+12.2%*	0.137	*-91.9%*
Total	12.877	16.145	*+25.4%*	0.830	*-93.6%*

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. A simulation of Hummock Pond with build out loading during a single cycle of breached and closed hydrodynamic conditions was run to compare with watershed loading under present conditions. The simulation includes a four-day period of tidal flushing followed by a 60-day period when the pond inlet is closed. An initial pond concentration of 0.60 mg/L was used at the point where the inlet is initially breached, which is within the typical range of the TN values in the measured data record before the spring opening. Because the watershed load increases by a moderate amount (25%), the increase in TN concentrations is also moderate for build out loading. TN concentrations at station HUM-3 increase from 0.857 mg/L with present conditions to 0.990 mg/L for build out at the end of the 64-day simulation period, as is seen in the results plotted in Figure VI-8. This represents a 21% increase in TN concentrations (compared to the background ocean TN concentration of 0.232 mg/L).

Table VI-5. Build-out conditions sub-embayment and surface water loads used for total nitrogen modeling of Hummock Pond, 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)
Hummock Pond main basin	14.258	1.918	0.196
Head of Hummock	1.888	0.208	1.454
Total	16.145	2.126	1.651

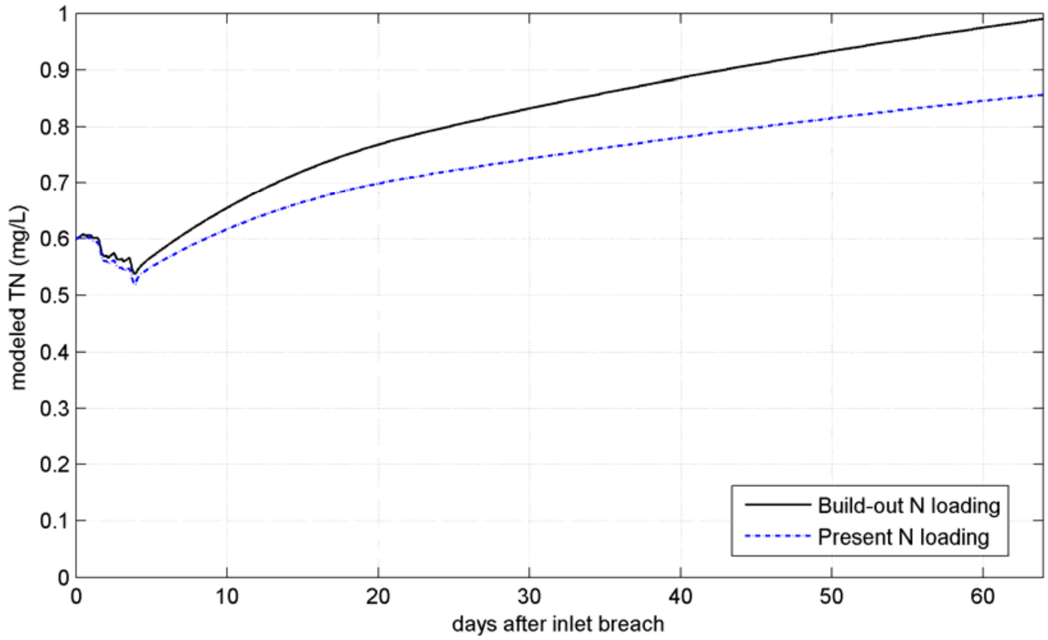

Figure VI-8. Modeled TN concentrations in the main basin of Hummock Pond (at monitoring stations HUM-3) after a simulated four-day open breach and its subsequent closure, with an initial concentration of 0.60 mg/L, for the build-out N loading scenario.

VI.2.5.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering the Pond for the modeled no anthropogenic loading scenario is presented in Table VI-6. Similar to what was done for build out conditions, a simulation of Hummock Pond with "no-load" loading during closed hydrodynamic conditions was run to compare with present conditions watershed loading. The simulation was run for 60 days, with an initial pond concentration of 0.60 mg/L, which is within the typical range of the TN values in the measured data record at the point of the spring opening. There is a large reduction in watershed load for the "no-load" scenario, which results in a similar drop in TN concentrations compared to present conditions. At the end of the 64-day simulation period, TN concentrations fall to 0.330 mg/L (Figure VI-9) in the main basin of the Pond with the "no-load" scenario, which is 0.527 mg/L less than for present conditions loading at this same monitoring station. This represents a 84% decrease in TN concentrations (compared to the background ocean TN concentration of 0.232 mg/L).

Table VI-6. No Anthropogenic conditions sub-embayment and surface water loads used for total nitrogen modeling of Hummock Pond, 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)
Hummock Pond main basin	0.693	1.918	0.065
Head of Hummock	0.137	0.208	0.312
Total	0.830	2.126	0.377

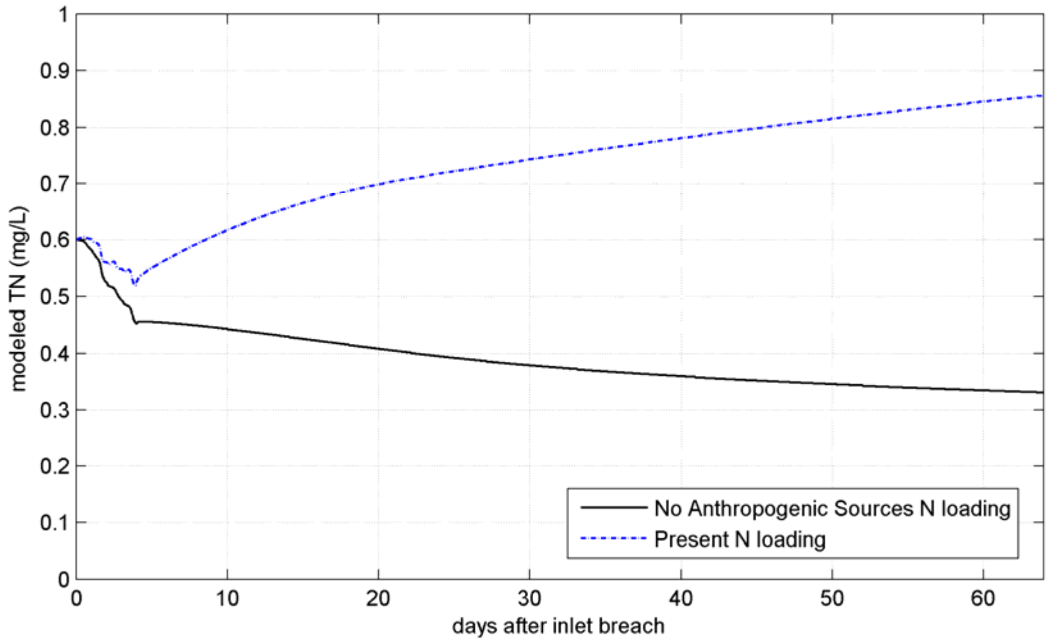

Figure VI-9. Modeled TN concentrations in the main basin of Hummock Pond (at monitoring stations HUM-3) after a simulated four-day open breach and its subsequent closure, with an initial concentration of 0.60 mg/L, for the no anthropogenic N loading scenario.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll-*a*, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Hummock Pond Embayment System (including Head of Hummock), the MEP assessment is based upon data from the water quality monitoring program developed by the Town of Nantucket, technical assistance from the Coastal Systems Program at UMD-SMAST for sampling in 2010 and 2012, as well as field survey and historical data collected under the programmatic umbrella of the Massachusetts Estuaries Project. These data typically include temporal surveys of eelgrass distribution (though not available for Hummock Pond); surveys of benthic animal communities and sediment characteristics; and time-series measurements of dissolved oxygen and Chlorophyll-*a* conducted during the summer and fall of 2007. 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 (Section VIII).

Part of the MEP assessment necessarily includes confirmation that the critical nutrient for management in any embayment is nitrogen and determination that a system is or is not impaired by nitrogen enrichment. Analysis of inorganic N/P molar ratios within the water column of the Hummock Pond Embayment System support the contention that nitrogen is the nutrient to be managed, as the average ratio over the entire Hummock Pond System (molar N/P ratio = 4.6) is well below the Redfield Ratio value (16) indicating that nitrogen additions will increase phytoplankton production, organic matter levels and turbidity within this system. Increased phytoplankton and organic matter levels increase oxygen consumption within the waters and sediments and increase the extent of oxygen depletion and habitat impairment. Similarly, N/P ratios for the Hummock Pond main basin range from 3.6 to 5.2, and for Head of Hummock (1.8), indicating that presently management should focus on nitrogen for restoration of impaired habitats within both the main basin and the small drown kettle of Head of Hummock. It should be noted that nitrogen enrichment occurs through two primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to limited tidal exchange with the low nitrogen waters of Nantucket Sound. Hummock Pond has seen increasing nitrogen loading from its watershed resulting from shifting land-uses and is very affected from restricted tidal exchange (two pond openings per year of variable duration). Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs.

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 threshold 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).

Results from these indicators were supported by observations of the distribution of macroalgal accumulations and sediment characteristics. 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 autonomous dissolved oxygen sensors in Hummock Pond at multiple (3) locations that would be representative of the dissolved oxygen conditions within Head of Hummock (upper mooring), the upper (middle mooring) and lower (lower mooring) reaches of the main basin of Hummock Pond. The dissolved oxygen and chlorophyll-*a* moorings were deployed to record the frequency and duration of low oxygen conditions and phytoplankton levels throughout 44 days of the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen overloading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Presence / absence of eelgrass beds within the Hummock Pond system was considered for comparison to historic records (MassDEP Eelgrass Mapping Program, C. Costello). Unfortunately, MassDEP has limited eelgrass information for the Hummock Pond Estuary as the embayment is closed to tidal exchange for the majority of the year preventing boat access. In addition, interpretation of aerial photographs yielded inconclusive results. The presence and temporal trends in the distribution of eelgrass beds are typically used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Although, eelgrass beds can decrease within embayments in response to a variety of causes, throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the Hummock Pond (including Head of Hummock) Embayment System, temporal changes in eelgrass distribution could not be established by the MassDEP Eelgrass Mapping program. However, review of historic maps and other information (Section VII.3) indicates that none of the basins comprising the Hummock Pond Estuary, supported significant eelgrass resources over the past 60 years.

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 (Sanders, H.L. 1960, Sanders, H.L. *et.al.*, 1980, Tian, Y.Q., J.J. Wang, J. A. Duff, B.L. Howes and A. Evgenidou. 2009) and New Bedford (Howes, B.L. and C.T. Taylor, 1990), 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 4 mg L^{-1}. Massachusetts State Water Quality

Classification indicates that SA (high quality) waters be able to maintain oxygen levels above 6 mg L^{-1}. The estuarine waters (periodically tidal during openings) of the Hummock Pond embayment 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 and that it is the designated water quality that is the target of TMDL's generated under the U.S. Clean Water Act. It is through the MEP and TMDL processes that site specific management targets are developed and under the Town's CWMP that management alternatives are designed 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, three (3) autonomously recording oxygen sensor was moored 30 cm above the embayment bottom within the main basins of the Hummock Pond system (Figure VII-2). The dissolved oxygen sensor (YSI 6600) was 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. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 43-44 days within the interval from August through late-September. All of the mooring data from the Hummock Pond system was collected during the summer of 2007.

Similar to other embayments in southeastern Massachusetts, the Hummock Pond Embayment System evaluated in this assessment showed high frequency variation in dissolved oxygen, related to diurnal influences as the pond was closed to tidal flows. 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 (daily range in DO). The high degree of temporal variation in bottom water dissolved oxygen concentration at mooring sites underscores the need for continuous monitoring within these systems.

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 44 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 for full evaluation of impacts of the current level of nitrogen enrichment.

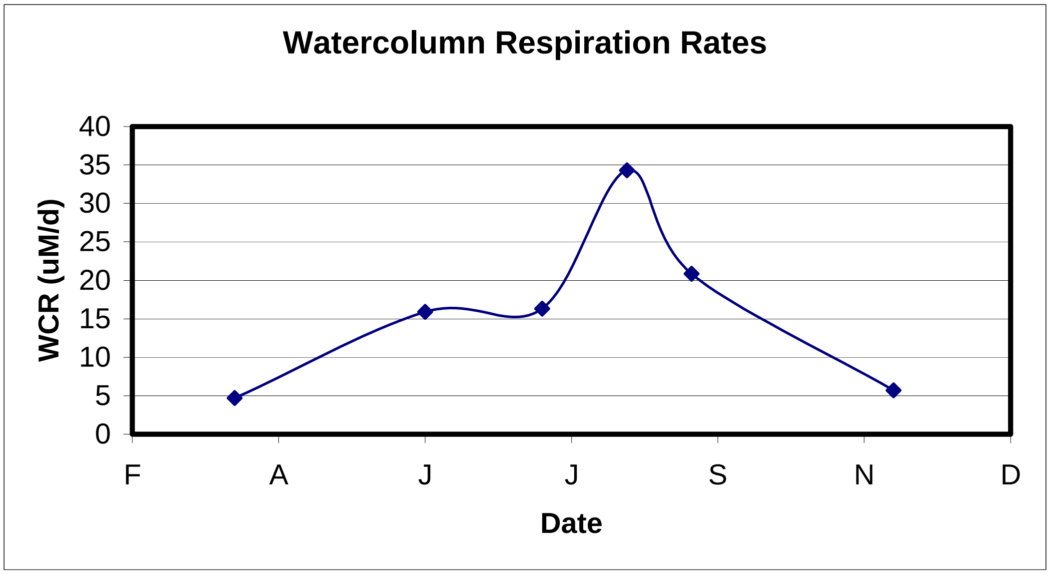

Figure VII-1. Example of typical average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System, Cape Cod (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate moderate to high nutrient enrichment of waters within the main basin (lower and mid gauges) of the Hummock Pond main basin with very high nutrient enrichment of the Head of Hummock (Figures VII-3 through VII-8). The oxygen data in the lower portion of the Hummock Pond main basin are consistent with low to moderate organic matter enrichment from phytoplankton production as seen from the parallel measurements of chlorophyll-*a* whereas oxygen data in the uppermost basin, Head of Hummock, are consistent with severe organic matter enrichment from phytoplankton production and deposition of SAV ("weeds") detritus. The measured levels of oxygen depletion and the spatial gradient observed in the chlorophyll-*a* levels parallel the magnitude and spatial pattern of total nitrogen levels throughout this system (Section VI).

The oxygen records obtained from Hummock Pond show that the lower main basin of the system has moderate daily oxygen excursions, indicative of moderate nitrogen enrichment which gradually increases moving towards Head of Hummock. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The evidence of oxygen levels slightly above atmospheric equilibration indicates that the main basin of the system is moderately nitrogen enriched whereas oxygen levels well above atmospheric equilibration in the Head of Hummock indicates this portion of the system is highly nitrogen enriched. However, in general in the lower portion of the main basin, the daily excursions reach upper concentrations approximating atmospheric equilibrium with a moderate number of significantly higher excursions, consistent with moderate nitrogen enrichment. Note that high levels of nitrogen enrichment can result in phytoplankton blooms that generate D.O. levels routinely in the 10-12 mg L^{-1} range or higher at mid-day as observed in the Head of Hummock.

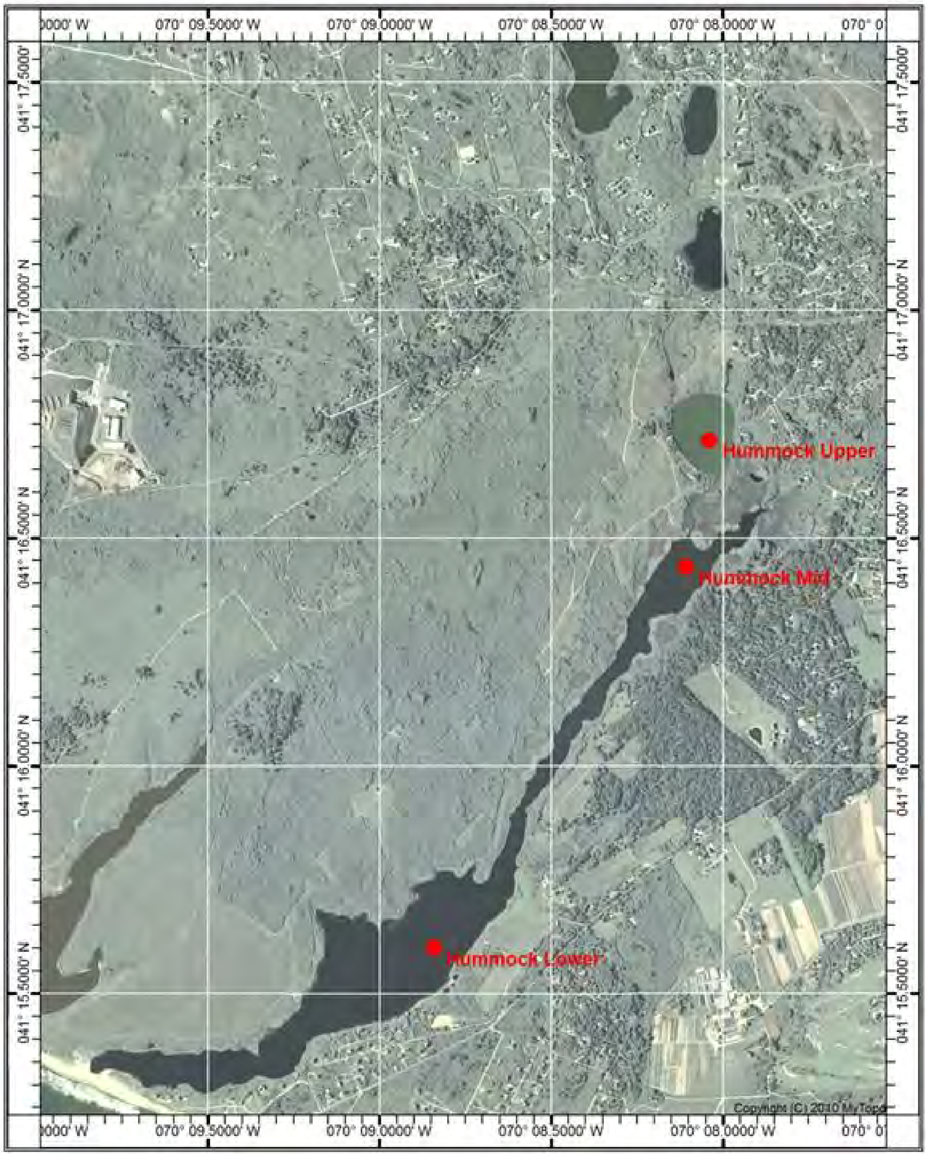

Figure VII-2. Aerial Photograph of the Hummock Pond embayment system in the Town of Nantucket showing the location of the continuously recording Dissolved Oxygen / Chlorophyll-*a* sensors deployed during the Summer of 2007.The gauge, "Hummock Pond Upper", is located in Head of Hummock, while the 2 other gauges are located within the upper and lower reaches of the main basin of Hummock Pond.

The embayment specific results are as follows:

Head of Hummock - Hummock Upper DO/CHLA Mooring (Figures VII-3 and VII-4):

The upper gauge in the Hummock Pond System was located in the central portion of the basin that constitutes the Head of Hummock basin (Figure VII-2). Significant daily excursions in oxygen levels were observed at this location, generally ranging from well above air equilibration (10-20 mg L^{-1}) to consistently below 3 mg L^{-1} (31% of record) and frequently to 0 mg L^{-1} (Figure VII-3, Table VII-1). Oxygen levels regularly exceeded 8 mg L^{-1} and even exceeded 15 mg L^{-1} for a period of approximately 7 days in the middle of the deployment period. These high oxygen levels result from the combined effects of high photosynthesis due to the high phytoplankton biomass and relatively poor flushing of this drown kettle basin in the upper Hummock Pond System. The high organic enrichment of the system is demonstrated by the high levels of phytoplankton biomass (chlorophyll a >25 ug L^{-1}, 100% of record), rates of photosynthesis (seen in the air equilibration values) and the severe declines in oxygen after sunset stemming from sediment and water column respiration.

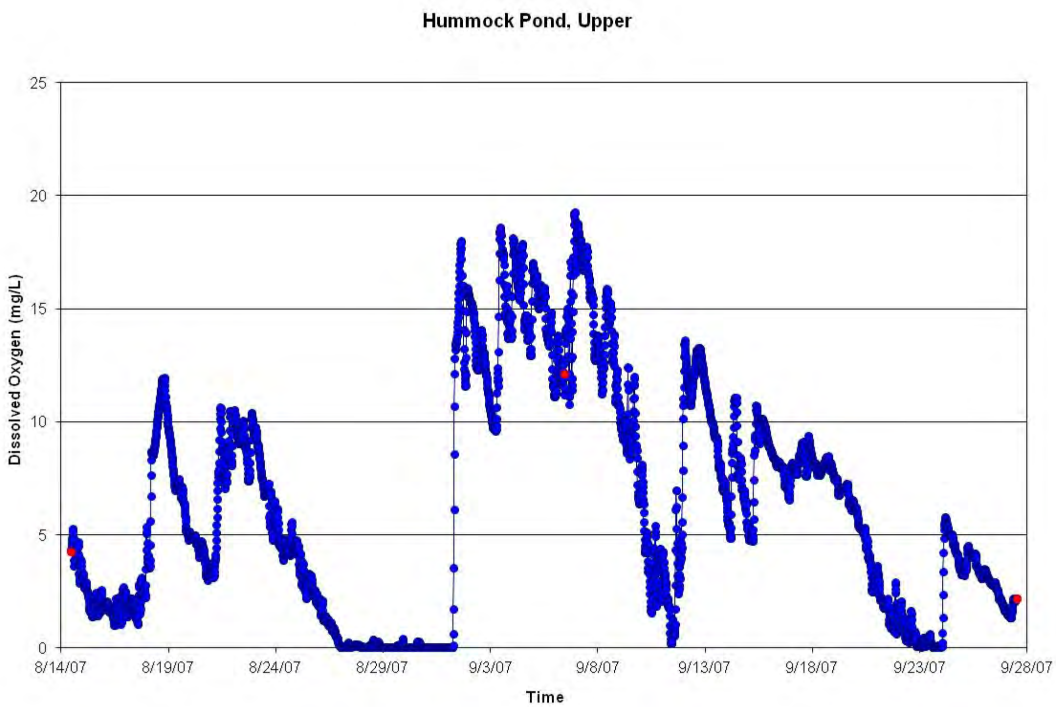

Figure VII-3. Bottom water record of dissolved oxygen in Head of Hummock (Hummock Pond upper station, Figure VII-2), Summer 2007. Calibration samples represented as red dots.

Over the 44 day deployment there were several significant phytoplankton blooms. The beginning of the deployment period captured a bloom in decline, but with high levels of chlorophyll over a 2-3 day period, around 30-40 ug L^{-1}, gradually declining to around 25 ug L^{-1} before another bloom occurred with chlorophyll-*a* going back up to between 50-60 ug L^{-1} and exceeding 60 ug L^{-1} for a short (~1-2 days) period (Table VII-2, Figure VII-4). The time-series record was consistent with the levels measured by the Water Quality Monitoring Program in 2010 and 2012 where the Head of Hummock Pond averaged ~50 ug L^{-1} during summer months. Measured chlorophyll-*a* levels far exceed the 10 ug L^{-1} average frequently used to indicate moderate nitrogen enrichment in coastal waters. The levels in the Head of Hummock show clear nitrogen enrichment and eutrophication.

The extreme levels of oxygen depletion and chlorophyll-*a* within the Head of Hummock basin indicate a system well beyond its nitrogen assimilative capacity, the level of nitrogen enrichment the system can assimilate without habitat impairment. This assessment is consistent with the levels of total nitrogen showing highly significant enrichment with the average long-term TN concentration for the basin of 1.63 mg N L^{-1} (Section VI), compared to TN levels of ~0.5 mg N L^{-1} typical of other coastal basins with healthy infaunal communities and no eelgrass habitat.

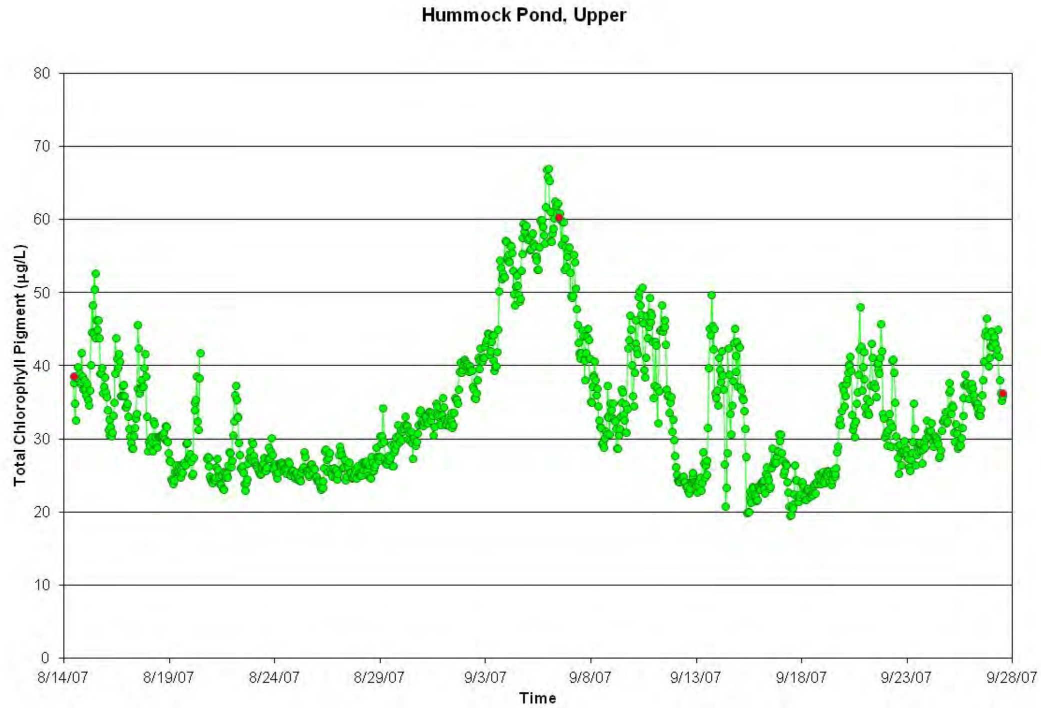

Figure VII-4. Bottom water record of Chlorophyll-*a* in the Hummock Pond upper station in Head of Hummock, Summer 2007. Calibration samples represented as red dots.

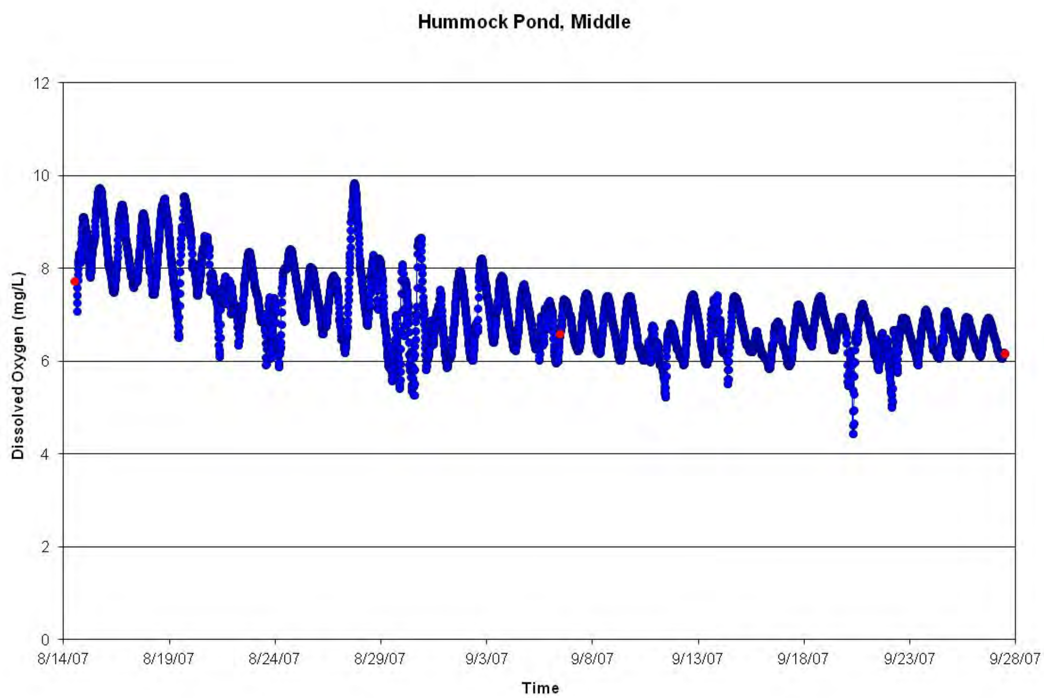

Figure VII-5. Bottom water record of dissolved oxygen at the Hummock Pond middle gauge, Summer 2007. Calibration samples represented as red dots.

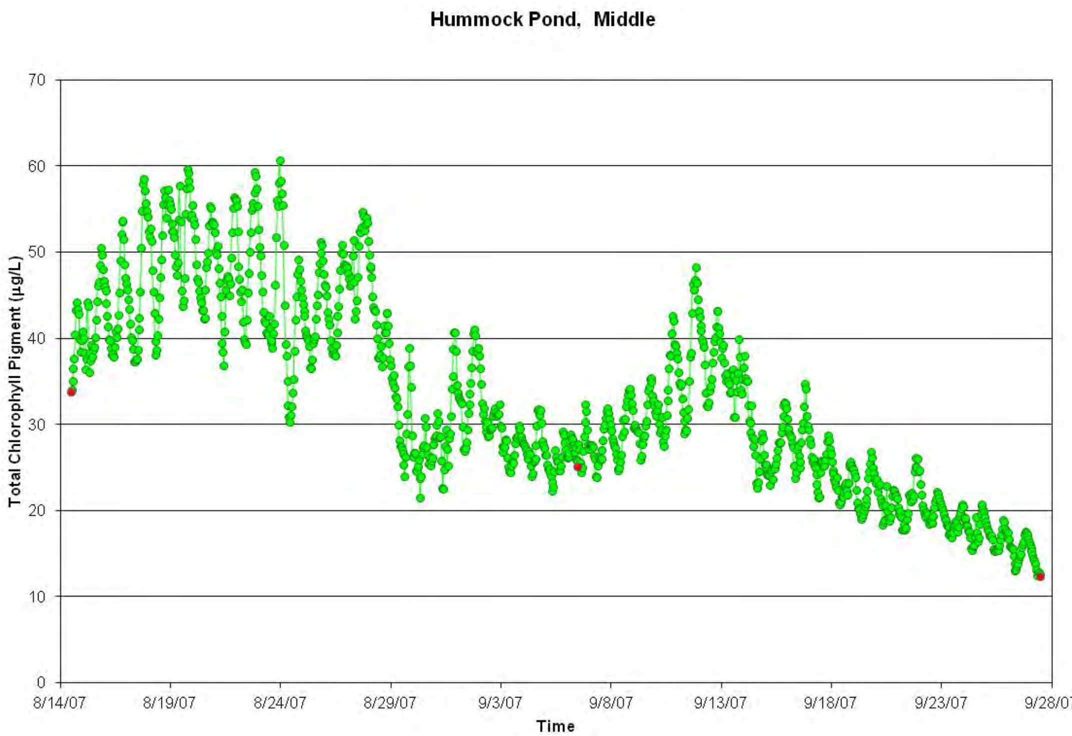

Figure VII-6. Bottom water record of Chlorophyll-*a* in the Hummock Pond middle gauge, Summer 2007. Calibration samples represented as red dots.

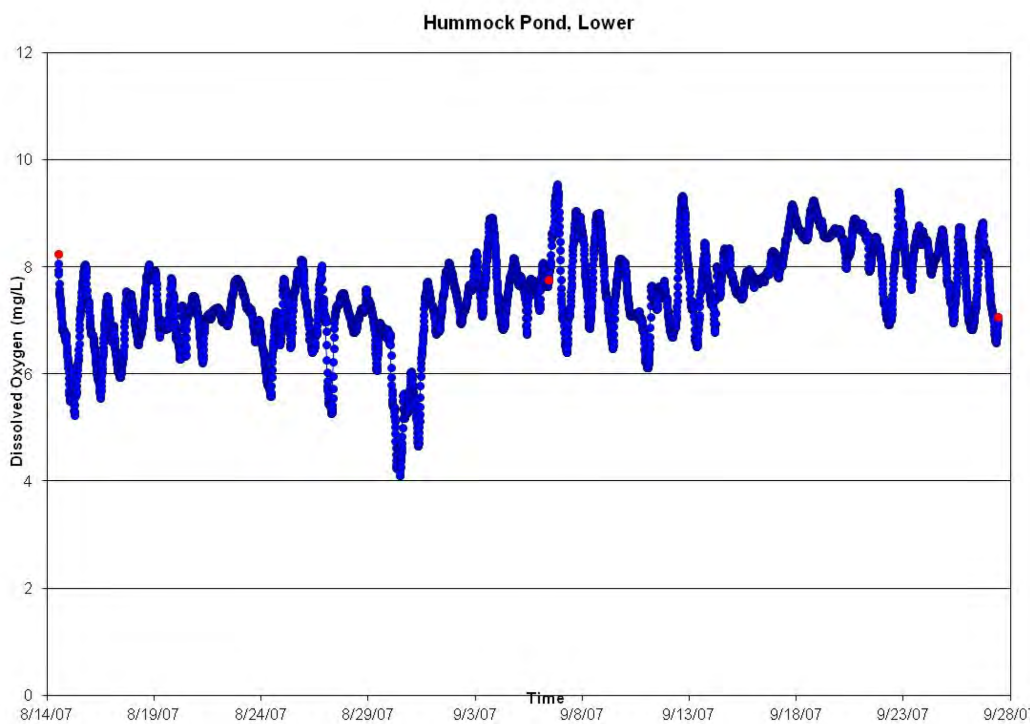

Figure VII-7. Bottom water record of dissolved oxygen at the Hummock Pond lower station, Summer 2007. Calibration samples represented as red dots.

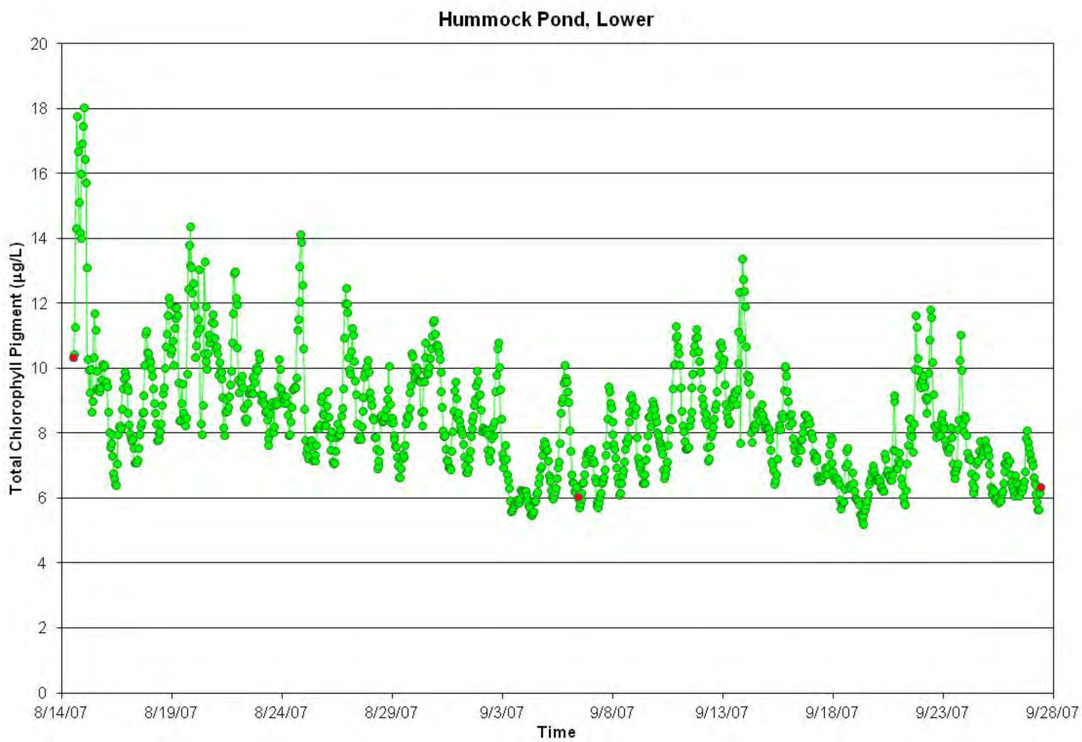

Figure VII-8. Bottom water record of Chlorophyll-*a* in the Hummock Pond lower station, Summer 2007. Calibration samples represented as red dots.

Hummock Pond Middle DO/CHLA Mooring (Figures VII-5 and VII-6):

The "middle" Hummock Pond instrument mooring was located in the upper narrow portion of the Hummock Pond main basin, just below the channel from the Head of Hummock basin. The mooring was located at the upper end of this narrow estuarine reach as depicted in Figure VII-2. In contrast to Head of Hummock, only moderate daily oxygen excursions were measured and oxygen levels were almost always 6 to 8 mg L^{-1}, with only rare depletions to 5 mg L^{-1} (Figure VII-5, Table VII-1). Daytime oxygen levels slightly exceeded 8 mg L^{-1} in the first week of the deployment, but rarely exceeded 9 mg L^{-1}. These moderate oxygen levels are likely the result of the combined effects of photosynthesis due to the high phytoplankton biomass (~50 ug L^{-1}) and poorly flushed water in the upper part of the Hummock Pond system. These features appear to be coupled with good atmospheric ventilation to maintain a relatively stable oxygen field even with the high phytoplankton biomass present. However, it is important to note that phytoplankton levels generally decreased over the duration of the deployment coupled with a decrease in the daily oxygen excursions.

Over the 44 day deployment chlorophyll-*a* levels averaged 33 ug L^{-1}, with two discernible phytoplankton blooms. The beginning of the deployment period showed elevated levels of chlorophyll over a 15 day period, where chlorophyll levels generally remained between 40-60 ug L^{-1}. Subsequent to this bloom period, chlorophyll levels declined to ~25 ug L^{-1} before a second smaller bloom occurred with chlorophyll levels peaking at ~40 ug L^{-1}. During the last two weeks of the deployment, chlorophyll levels steadily declined to ~10 ug L^{-1} by the end of the record. The time-series record was consistent with the levels measured by the Water Quality Monitoring Program where the upper Basin averaged 20-30 ug L^{-1} during summer months. Chlorophyll-*a* levels over 10 ug L^{-1} have been used to indicate moderate nitrogen enrichment in embayments. The levels in this upper portion of the Hummock Pond system are high for enclosed basins during summer.

The moderate levels of oxygen depletion but high chlorophyll-*a* within the Hummock Pond upper basin (mid-mooring location) indicates a system beyond its nitrogen assimilative capacity, the level of nitrogen enrichment the system can assimilate without habitat impairment. This assessment is consistent with the levels of total nitrogen showing only moderate enrichment with the average long-term TN concentration for the basin of 0.82 mg N L^{-1} (Section VI), compared to TN levels of ~0.5 mg N L^{-1} typical of other coastal basins with healthy infaunal communities and no eelgrass habitat.

Hummock Pond Lower DO/CHLA Mooring (Figures VII-7 and VII-8):

The Hummock Pond (lower) instrument mooring was centrally located in the lower reach of the Hummock Pond main basin (Figure VII-2). Moderate daily excursions in oxygen levels were observed at this location, generally ranging between 6 mg L^{-1} and 8 mg L^{-1} and rarely to 5 mg L^{-1} (Figure VII-7, Table VII-1). Oxygen levels consistently exceeded 8 mg L^{-1} during the second half of the deployment period but rarely exceeded 9 mg L^{-1}. These moderate oxygen levels are likely the result of the combined effects of low photosynthesis due to the low phytoplankton biomass in this portion of the overall system. The lower organic enrichment of this part of the system is demonstrated by the low rates of photosynthesis (seen in the air equilibration values) and the moderate declines in oxygen after sunset stemming from sediment and water column respiration.

Over the 44 day deployment no definable phytoplankton blooms were observed and chlorophyll-*a* levels generally remained below 12 ug L^{-1} and for most of the record was between 6-10 ug L^{-1}. The average over the 44 day deployment was only 8.4 ug L^{-1}, exceeding the 10 ug L^{-1} benchmark only 16% of the time (Table VII-2, Figure VII-8). The time-series record was consistent with the levels measured by the Water Quality Monitoring Program where the Hummock Pond lower basin averaged 9 ug L^{-1} during summer months. Chlorophyll-*a* levels over 10 ug L^{-1} have been used to indicate moderate nitrogen enrichment in embayments. The levels in the lower portion of the Hummock Pond system are relatively low for enclosed basins during summer.

The low-moderate levels of oxygen depletion and chlorophyll-*a* within the Hummock Pond lower main basin indicate a system at or near its nitrogen assimilative capacity, the level of nitrogen enrichment the system can assimilate without habitat impairment. This assessment is consistent with the levels of total nitrogen showing moderate-high enrichment with the average long-term TN concentration for the basin of ~0.72 mg N L^{-1} (Section VI). This level of water column TN and that in the upper tidal reaches of the estuary are generally associated with impaired benthic animal habitat, including reduced numbers of individuals and species, in other embayments throughout the region.

Table VII-1. Days and percent of time during deployment of *in situ* sensors that bottom water oxygen levels were below various benchmark oxygen levels within the Hummock Pond (including Head of Hummock) Embayment System.

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Hummock Pond, Lower	**8/14/2007**	**9/27/2007**	**43.9**	**6%**	**1%**	**0%**	**0%**
			Mean	0.32	0.22	NA	NA
			Min	0.07	0.10	0.00	0.00
			Max	0.90	0.34	0.00	0.00
			S.D.	0.25	0.17	NA	NA
Hummock Pond, Middle	**8/14/2007**	**9/27/2007**	**43.9**	**5%**	**0%**	**0%**	**0%**
			Mean	0.09	0.04	0.01	0.01
			Min	0.01	0.01	0.01	0.01
			Max	0.32	0.06	0.01	0.01
			S.D.	0.07	0.04	NA	NA
Hummock Pond, Upper	**8/14/2007**	**9/27/2007**	**44.1**	**36%**	**42%**	**37%**	**31%**
			Mean	1.45	1.03	0.81	0.76
			Min	0.01	0.01	0.01	0.02
			Max	8.21	7.54	7.15	6.61
			S.D.	2.50	1.96	1.78	1.71

Table VII-2. Duration (days and % of deployment time) that chlorophyll-*a* levels exceed various benchmark levels within the Hummock Pond (including Head of Hummock, "upper") Estuary. "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.

Mooring Location	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)
Hummock Pond, Lower	**8/14/2007**	**9/27/2007**	**43.9**	**100%**	**16%**	**1%**	**0%**	**0%**
Mean Chl Value = 8.4 ug/L			Mean	21.96	0.21	0.19	NA	NA
			Min	0.04	0.04	0.13	0.00	0.00
			Max	43.88	0.63	0.25	0.00	0.00
			S.D.	30.99	0.18	0.09	NA	NA
Hummock Pond, Middle	**8/14/2007**	**9/27/2007**	**43.9**	**100%**	**100%**	**99%**	**88%**	**75%**
Mean Chl Value = 33.1 ug/L			Mean	44.00	44.00	21.63	4.81	1.57
			Min	44.00	44.00	0.50	0.08	0.04
			Max	44.00	44.00	42.75	35.79	15.08
			S.D.	NA	NA	29.88	12.52	3.38
Hummock Pond, Upper	**8/14/2007**	**9/27/2007**	**43.875**	**99%**	**99%**	**99%**	**99%**	**85%**
Mean Chl Value = 33.9 ug/L			Mean	43.63	43.63	43.63	14.49	1.01
			Min	43.63	43.63	43.63	1.96	0.04
			Max	43.63	43.63	43.63	31.46	14.54
			S.D.	NA	NA	NA	15.24	2.71

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Recent eelgrass surveys were not undertaken for the Hummock Pond system by the MassDEP Eelgrass Mapping Program (C.Costello), as the pond is a closed system and inaccessible to the MassDEP Eelgrass Mapping Program. In an attempt to determine whether or not there may have been eelgrass in Hummock Pond as far back as 1951, analysis of available aerial photos from 1951 was obtained to attempt a reconstruction of the eelgrass distribution prior to any substantial development of the watershed. Unfortunately, the 1951 aerial photographs were un-interpretable 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 within the Hummock Pond Estuary is not likely as the Pond has been closed to regular tidal exchange as far back as the 1930's with barrier beach openings only occurring once or twice per year. A review of available records did not reveal any evidence of eelgrass in the main basin of Hummock, most likely due to its dynamic inlet resulting in periodic loss of tidal exchange, historically and today, and resulting in poor water quality.

Eelgrass surveying was conducted in Hummock Pond by MEP Technical Team members in 2007. Grab samples of the bottom and visual surveys by SCUBA divers in multiple locations along the length of the Pond did not reveal the presence of eelgrass, however, divers did observe the presence of macroalgae at multiple sediment sampling station locations in the lower basin of the system before it narrows mid-way up towards the Head of Hummock Pond. This is not surprising as the salinity in Hummock Pond tends to below in between openings and not supportive of eelgrass.

Prior to the 2007 MEP assessment of eelgrass presence/absence in Hummock Pond, a survey of aquatic vegetation in Hummock Pond was undertaken for the Hummock Pond Association (2005-2006). The purpose of the annual report was to summarize the submerged aquatic weed situation in Hummock Pond for members of the Hummock Pond Association (HPA). The summary document contained a "weed" inventory with pictures of the types of SAV observed as well as several figures (Figure VII-13 and VII-14) denoting the spatial extent of the observed SAV.

As indicated in the report, in general there were fewer attached, submerged weed in 2006 than in 2005 and no invasive, non-native species were found in Hummock Pond. The reason for fewer weeds in 2006 could be attributable to a number of factors such as available nutrients, average temperature, available sunlight or water clarity. However, no definitive conclusions as to the cause were provided in the report.

According to the report submitted to the Hummock Pond Association, during October of 2006 an inventory was made of the species of weeds in Hummock Pond. The reason for inventorying the major species was to try to determine if any invasive or non-native species had colonized the Pond. During the annual inventory the general location of the species of weeds were marked on a topographic map, so that comparisons could be made from year to year. The major weed species and their approximate location in the Pond in 2005 and October of 2006 are shown in Figures VII-9 through VII-12.

Additionally, pictures of the various species of weeds were taken both out of the Pond and in the Pond and were provided in the report and reproduced herein.

Figure VII-9. Redhead Pondgrass, mixed Redhead Pondgrass and Sago Pondweed.

Figure VII-10. Sago Pondweed.

Figure VII-11. Eel Grass.

The suggestion that eelgrass existed in 2006, is not seen as definitive and certainly there were no eelgrass beds present. The provided photograph of SAV, shows highly epiphytized plants, and it is difficult to determine eelgrass. The MEP concluded based on the environmental conditions, and level of delineation, that significant eelgrass habitat could not be documented with confidence to exist, either historically or presently, within Hummock Pond. However, this prompted further review of historic maps and information that indicate that none of the basins comprising the Hummock Pond Estuary, were likely to have supported significant eelgrass resources over the past 60 years. First, Head of Hummock appears to have been connected to Hummock Pond via an artificial channel, therefore it is a transformed freshwater kettle pond, rather than a natural estuarine basin. As such, it would not have historically supported eelgrass. In addition, a review of available records did not reveal any evidence of eelgrass beds in the main basin of Hummock, most likely due to its dynamic inlet resulting in periodic loss of tidal exchange, historically and today, and resulting poor water quality. Historical eelgrass beds have not been found in other embayments with similar inlet closures, throughout the region, although ephemeral patches may occur during periods of prolonged or frequent tidal exchange (e.g. Tisbury Great Pond). Equally significant, under present salinity conditions, Head of Hummock is below the lowest salinity where eelgrass is found to grow (5 ppt), and Hummock Pond is periodically below or just above that level as well. Therefore, only at higher salinity levels would eelgrass colonization even be possible in this system. It should also be noted that eelgrass beds throughout the regions are typically found at salinities within the 20-32 ppt range.

Figure VII-12. Coontail.

The Weed Study conducted by the Hummock Pond Association provides additional support for the prolonged low salinity of the waters in Head of Hummock and in the upper reach of the main basin of Hummock Pond, as many of the plants have a low tolerance for salt water, generally less than the 5 ppt lower limit for eelgrass growth.

Based upon these multiple lines of evidence, it appears that the basins comprising the Hummock Pond Estuary have not historically supported eelgrass beds or significant eelgrass habitat. Therefore, the threshold analysis for this system is necessarily focused on restoration/protection of infaunal animal habitat. However, to the extent that nitrogen management of the watershed is necessary, it will also be protective of eelgrass habitat and infaunal habitat within the down-gradient near shore waters of the Atlantic. This down-gradient effect, to the extent that it occurs, will be a by-product of any nitrogen management of the embayment, but is not part of the thresholds analyses for this system.

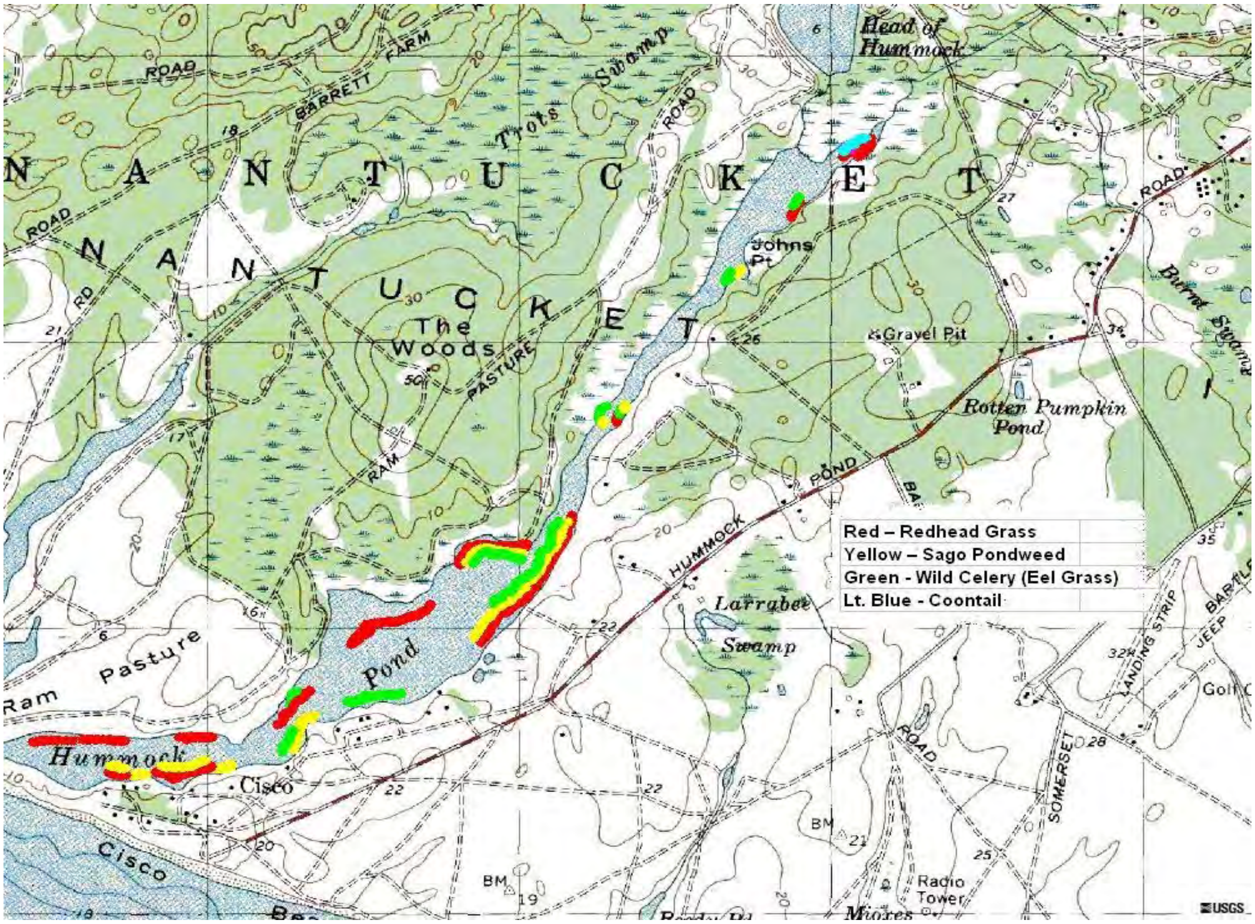

Figure VII-13. Submerged aquatic vegetation survey of the Hummock Pond embayment system showing location of different types of aquatic vegetation observed in 2005 (courtesy of Hummock Pond Association - 2006 Weed Inventory Map). This map and associated data can be obtained by contacting Bob Williams, President HPA, rwilliams@npb.com or Toni Moores, "Chief Weed Watcher" HPA, tonimoores@comcast.net.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 11 locations within the Hummock Pond System (Figure VII-15), with replicate assays at each site. In all areas and particularly those that do not support eelgrass beds, 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 as there is no quantifiable evidence of eelgrass colonizing Hummock Pond, any nitrogen management of this embayment system should focus on benthic animal habitat. While

Hummock Pond appears to have not supported eelgrass beds in the past 70-80 years given its closed status and extremely limited tidal exchange, 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).

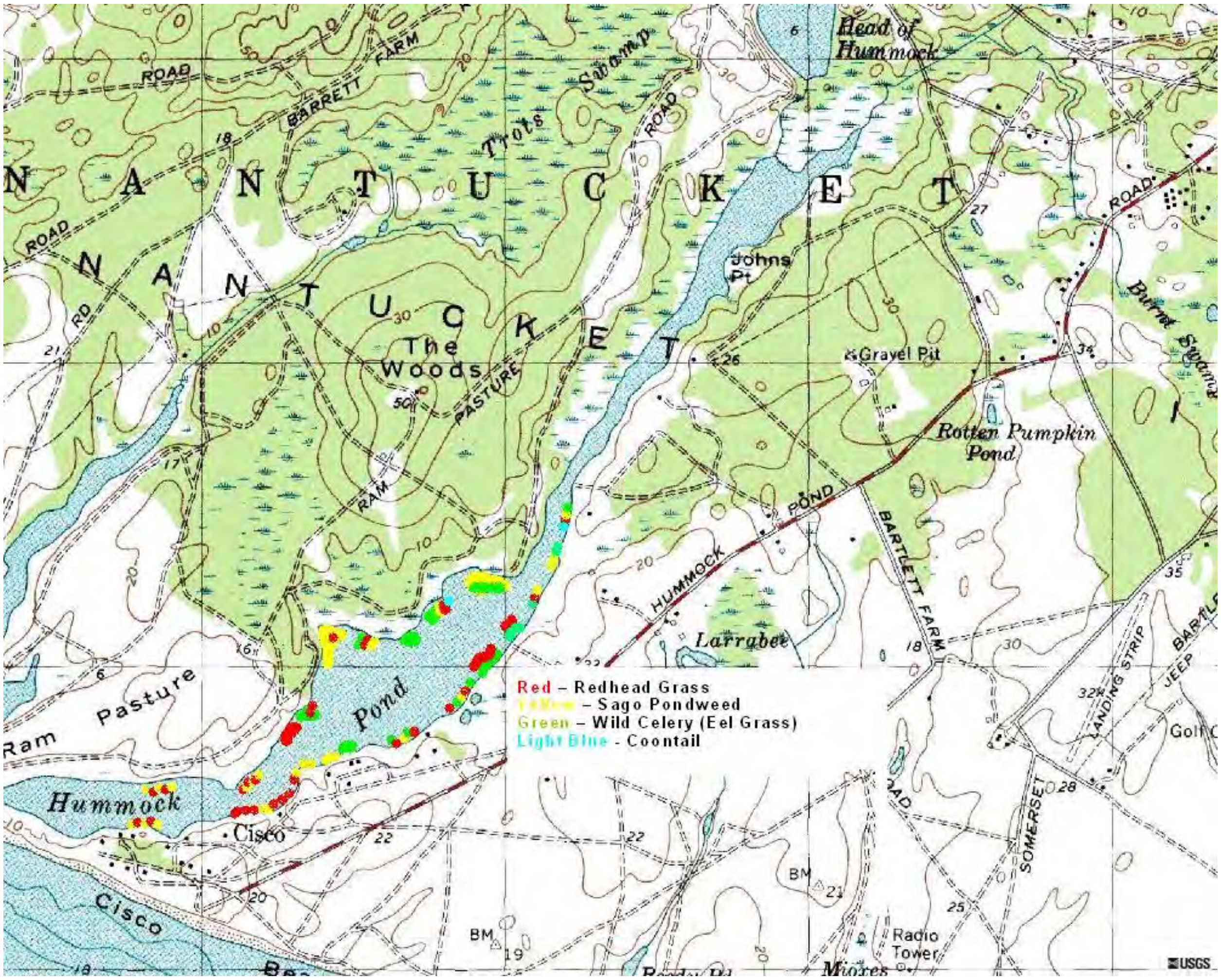

Figure VII-14. Submerged aquatic vegetation survey of the Hummock Pond embayment system showing location of different types of aquatic vegetation observed in 2006 (courtesy of Hummock Pond Association - 2006 Weed Inventory Map). This map and associated data can be obtained by contacting Bob Williams, President HPA, rwilliams@npb.com or Toni Moores, "Chief Weed Watcher" HPA, tonimoores@comcast.net.

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-*a* 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.

Figure VII-15. Aerial photograph of the Hummock Pond embayment system showing location of benthic infaunal sampling stations (yellow symbols) within the main pond basin and Head of Hummock Pond.

Overall, the benthic infauna survey indicated that the main basin of Hummock Pond is supporting a gradient in impairment from significantly impaired in the upper basin to moderately impaired in the lowest reach near the barrier beach. However, the tributary basin of Head of Hummock is currently supporting severely degraded habitat with no marine invertebrates and only 2 species of insect larvae. Head of Hummock contains lower salinity water than the Hummock Pond main basin, likely due to its function as a drown kettle pond in the uppermost reach of the system. As such, Head of Hummock is the focus of groundwater discharge from the watershed and as the entire system is usually without tidal currents, mixing is limited. The salinity of Head of Hummock is low enough (<5 ppt) to influence the plant and animal species present, although estuarine benthic animal communities are fully capable of colonizing at salinities to 3 ppt. However, the Head of Hummock basin is virtually devoid of benthic animals, only supporting 2 insect larval species and no estuarine infauna. In contrast, the main basin of Hummock Pond, does currently support benthic animal communities, even in the same salinity range as Head of Hummock. Therefore, the loss of benthic animals in Head of Hummock appears to be related to the high organic matter loading and periodic anoxia, rather than the low salinity (as was also observed in Oyster Pond, Falmouth).

The main basin of Hummock Pond is presently supporting significantly impaired benthic animal habitat in its upper reaches with low numbers of species (4) and individuals (~90) and with a moderate to low diversity (1.6) (Table VII-3). Significantly, stress indicator species (Capitellids, Tubificids) are not prevalent at any station within the main basin, comprising a minor fraction (<2%) of the population. Benthic habitat quality improves moving toward the barrier beach with the lower main basin having moderate numbers of species (8) and individuals (~120) but still moderate to low diversity (1.8). Similarly, in the basin nearest the barrier beach, habitat is only showing moderate impairment with moderate numbers of species (10) and individuals (~200) and diversity (2.3). Both the values of the habitat indicators and the gradient in quality from upper to lower estuary, are consistent with the observed levels of oxygen depletion (periodic anoxia in Head of Hummock), organic enrichment (chlorophyll-*a* at 40-60 ug L^{-1}) in Head of Hummock and <10 ug L^{-1} in the lower main basin of Hummock Pond. The gradient in habitat quality also parallels the TN levels of 1.6 mg N L^{-1} declining to ~0.7 mg N L^{-1} in the lower main basin. This range in TN has been found to support only impaired benthic animal habitat in open water systems throughout southeastern Massachusetts. Further evidence of impairment of the main basin of Hummock Pond is the dominance of the benthic community by amphipods (*Ampelisca, Leptocheiris*), which are typical of transitional environments (between high and low quality habitat).

Table VII-3. Benthic infaunal community data for the Hummock Pond Embayment System (inclusive of Head of Hummock). 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 0.0625 m2). Stations refer to map in Figure VII-15, Head of Hummock is fresher than Hummock Pond and was colonized by insect larvae (chironomidae, chaoboridae) not estuarine benthic animals. Note the clear gradient in habitat quality from the uppermost to lowermost regions.

	Sta. I.D.*	Total Species	Total Individuals	#Species Calc @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Hummock Pond Estuarine System						
Inlet Basin	**1,2**	**10**	**187**	**9**	**2.32**	**0.69**
Lower Main Basin	**4,5,6,7**	**8**	**118**	**7**	**1.77**	**0.62**
Upper Main Basin	**11,12,13,15**	**4**	**91**	**3**	**1.63**	**0.77**
Head of Hummock	**9**	**2**	**88**	**2**	**0.81**	**0.81**
* Station i.d.'s refer to Figure VII-10.						

In addition to the water column indicators, the lower basin of Hummock Pond has accumulations of macroalgae along the margins of the basin which are associated with poor benthic habitat. Macroalgae can have a "smothering" effect on benthic animals as observed in the most extreme situation of the main basin of Waquoit Bay. The accumulations result in low oxygen at the sediment surface resulting in decline of benthic populations. These accumulation in the lower main basin provide additional stress to benthic communities and are consistent with the observed TN level and observed benthic communities.

The benthic animal communities within the basins of the Hummock Pond System were compared to high quality environments, such as the Outer Basin of Quissett Harbor, which provides additional confirmation of impaired habitat. The Outer Basin of Quissett Harbor supports benthic animal communities with $\geq$28 species, >400 individuals with high diversity (H' $\geq$3.7) and Evenness (E $\geq$0.77). Similarly, outer stations within Lewis Bay in Barnstable currently support similarly high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Eveness (0.74). Equally important these communities are not consistent with nutrient enrichment being composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms (tubificids, capitellids). These habitats represent the highest quality and exist in well flushed basins and have consistently high oxygen and low chlorophyll a levels and low amounts of organic enrichment. While these represent a theoretical goal for restoration, the reality of the tidal flushing characteristics of Hummock Pond must also be taken into account, as with other periodically opened estuaries (Edgartown Great Pond, Tisbury Great Pond).

Overall, the pattern of infaunal habitat quality throughout the Hummock Pond Estuary is consistent with measured dissolved oxygen concentration, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily includes the structure of the specific estuarine basin and its tidal characteristics (continuously or periodically opened to tidal flows). Based upon this analysis it is clear that the upper regions of the estuary, Head of Hummock and upper main basin of Hummock Pond, are severely degraded and significantly impaired, respectively, by nitrogen and organic matter enrichment while the lower main basin is presently supporting moderately impaired benthic animal habitat. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the upper basin (Head of Hummock) 1.0 mg N L^{-1}, a level associated with significant impairment of benthic animal habitat in other southeastern Massachusetts estuaries.

The benthic habitat quality throughout the Hummock Pond Estuary is fully consistent with findings from other estuaries in the region with similar TN, chlorophyll-*a* and oxygen levels. In general, TN levels >0.7 mg N L^{-1} have been documented to be associated with impaired benthic communities, while levels >1 mg N L^{-1} typically are severely degraded and have lost most of animal habitat, with the proximate cause typically low oxygen levels due to high organic matter enrichment. As there is no evidence of present or historic eelgrass beds within the Hummock Pond Estuary, management actions should focus on restoration of benthic animal habitat.

Other Benthic Resources:

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the propagation of shellfish (Figure VII-16). While the waters offshore of Hummock Pond were classified as approved for shellfishing, the enclosed waters of Hummock Pond were not classified by the Division of Marine Fisheries, making it unclear as to whether or not Hummock Pond is an approved shellfishing environment. Unlike other systems in the MEP study region, the Hummock Pond system has also NOT been classified specifically for its support of specific shellfish communities, therefore, the MEP habitat assessment has relied heavily on infaunal data collection completed by the MEP technical team.

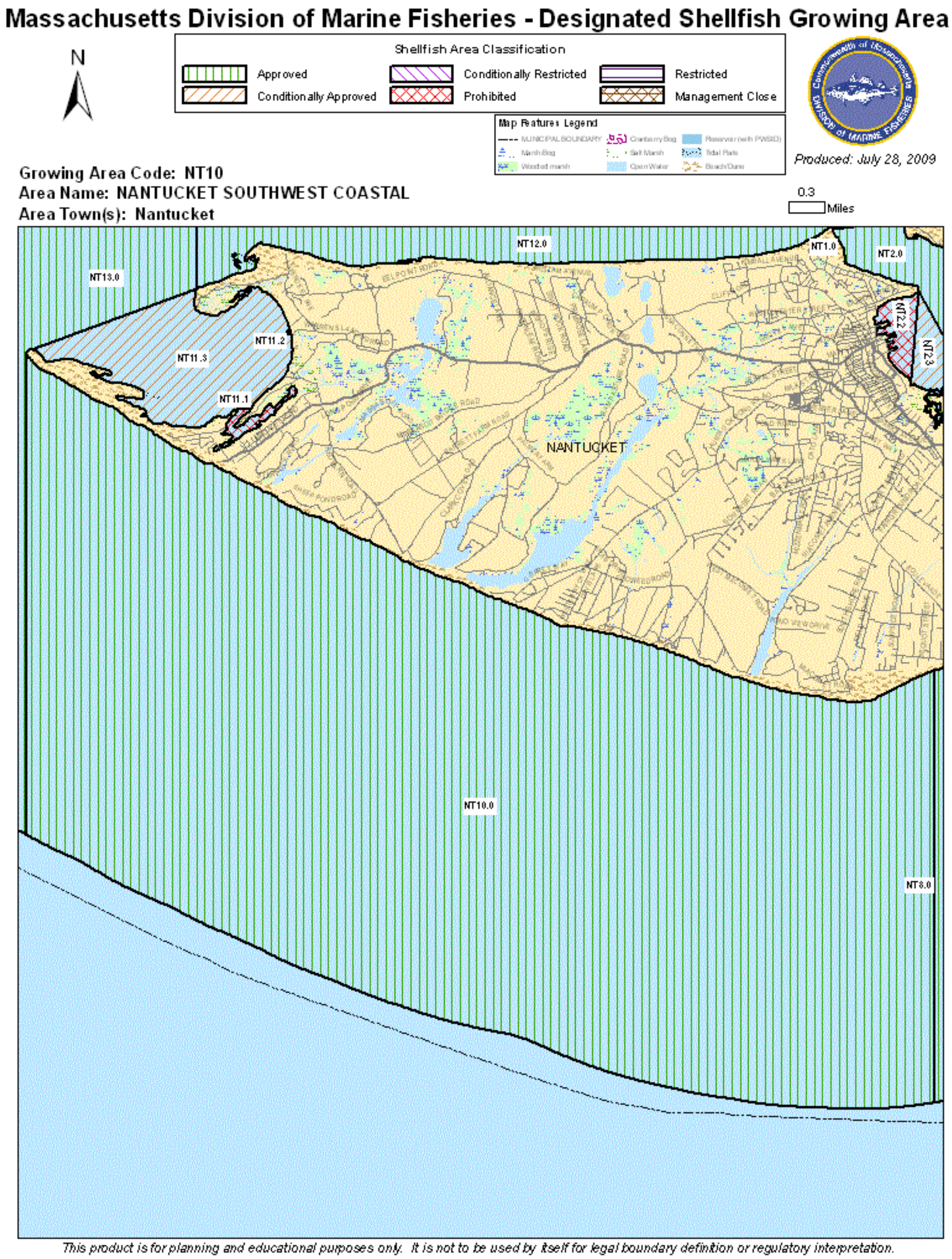

Figure VII-16. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

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). Additional information on temporal changes within each sub-embayment of an estuary and its associated watershed nitrogen load further strengthen the analysis. These data were collected to support threshold development for the Hummock Pond Estuarine System by the MEP 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 baseline Water Quality Monitoring Program conducted by Town staff and by staff and graduate researchers at and with analytical support from the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

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 associated watershed nitrogen load and geomorphological considerations of basin depth, stratification and functional type further strengthen the analysis. These data were collected to support threshold development for the Hummock Pond Estuarine 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 and analytical support from the Coastal Systems Program at SMAST-UMass Dartmouth.

The Hummock Pond Estuary is comprised of two major functional units, each with different levels of habitat quality, both are brackish (varying from 4-8 ppt). The main basin of Hummock Pond (e.g. the drown valley formed perpendicular to the barrier beach) which is generally closed to tidal exchange, and opened by breaching the barrier beach twice per year for pond management. Hummock Pond is a shallow narrow "finger pond" with moderate-significant impairment of benthic animal habitat and no historic eelgrass coverage. The second unit, Head of Hummock, is a man-altered basin which was once a freshwater kettle pond which has a channel to Hummock Pond which now allows salt water to enter. Head of Hummock supports severely degraded benthic animal habitat and no historic eelgrass coverage. The salinity of Head of Hummock and possibly Hummock Pond are at the limit for grow of eelgrass (5 ppt) consistent with the lack of eelgrass coverage historically. There is a clear gradient in infaunal habitat quality from severely degraded conditions in Head of Hummock to the lower main basin of Hummock Pond adjacent the barrier beach having the highest quality habitat.

Part of the MEP assessment of the Hummock Pond Estuarine System was confirmation that the critical parameter controlling habitat quality is nitrogen, hence managing nitrogen enrichment would result in restoration of observed impairments. Analysis of inorganic N/P molar ratios within the water column of the Hummock Pond Estuarine System are consistent with virtually all of the estuaries in southeastern Massachusetts and New England in that nitrogen is the critical nutrient to be managed. The measured Redfield Ratio (inorganic N/P) ranges from 3.6-5.2 within the main basin and 1.8 within Head of Hummock. These data and the low concentration of inorganic nitrogen (~0.03 mg L^{-1}) indicate that nitrogen additions will increase phytoplankton production, organic matter levels and turbidity within this system.

Increased phytoplankton and organic matter levels increase oxygen consumption within the waters and sediments and increase the extent of oxygen depletion and habitat impairment. It should be noted that nitrogen enrichment occurs through two primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with low nitrogen offshore waters. The Hummock Pond Estuary has seen increasing nitrogen loading from its watershed from shifting land-uses and due to coastal processes along its barrier beach, it is only periodically opened to tidal exchange. Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs. Decreasing watershed nitrogen inputs or increasing tidal flushing will reduce nitrogen enrichment and its impacts. The present distribution and level of benthic animal habitat quality observed within the estuary is consistent with degree of nitrogen enrichment, and its resulting increase in phytoplankton biomass, organic matter and oxygen levels. All of the habitat indicators are consistent with the above assessment of the whole of the Hummock Pond System (Chapter VII).

At present, eelgrass beds are not present in the Hummock Pond Estuary. The absence of eelgrass beds within Hummock Pond is expected given the measured levels of nitrogen enrichment and resulting chlorophyll a and dissolved oxygen. Total nitrogen levels (TN) within the lower basin have mean summer time levels >0.7 mg N L^{-1} compared to the levels in other similarly configured southeastern Massachusetts estuarine basins currently supporting eelgrass, 0.35-0.45 mg N L^{-1} (range of Cape Cod systems). Other key water quality indicators, dissolved oxygen and chlorophyll a, show similar levels of enrichment with chlorophyll levels averaging 9 to 33 ug L^{-1} in lower and upper reaches of main basin. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, the lack of eelgrass habitat within Hummock Pond is consistent with observed eelgrass habitat and areas of loss in numerous other estuaries throughout the region. While Hummock Pond lacks eelgrass habitat, benthic animal habitat is also a critical estuarine resource and it is impaired throughout the Hummock Pond Estuary. Benthic animal habitat is generally has a higher tolerance for nitrogen enrichment than eelgrass, as unlike eelgrass, benthic animals do not require light for growth and therefore higher levels of turbidity and phytoplankton biomass are tolerated. Infauna habitat quality is the primary habitat for management of the basins comprising eh Hummock Pond Estuary.

The is also no evidence that Hummock Pond supported eelgrass coverage over the past 60 years. Review of historic maps and information that indicate that none of the basins comprising the Hummock Pond Estuary were capable of supporting eelgrass historically. First, Head of Hummock appears to have been connected to Hummock Pond via an artificial channel, therefore it is a transformed freshwater kettle pond, rather than a natural estuarine basin. As such, it would not have historically supported eelgrass. In addition, a review of available records did not reveal any evidence of eelgrass beds in the main basin of Hummock, most likely due to its dynamic inlet resulting in periodic loss of tidal exchange, historically and today, and resulting poor water quality. Historical eelgrass beds have not been found in other embayments with similar inlet closures, throughout the region, although ephemeral patches may occur during periods of prolonged or frequent tidal exchange (e.g. Tisbury Great Pond). Equally significant, under present salinity conditions, Head of Hummock is below the lowest salinity where eelgrass is found to grow (5 ppt), and Hummock Pond is periodically below or just above that level as well. Only at higher salinity levels would eelgrass colonization even be possible in this system and the nature of the inlet makes this occurance unlikely over any prolonged period.. It should also be noted that eelgrass beds throughout the regions are typically found at salinities within the 20-32 ppt range.

The Weed Study conducted by the Hummock Pond Association provides additional support for the prolonged low salinity of the waters in Head of Hummock and in the upper reach of the main basin of Hummock Pond, as many of the plants found have a low tolerance for salt water, generally less than the 5 ppt lower limit for eelgrass growth.

Based upon these multiple lines of evidence, it appears that the basins comprising the Hummock Pond Estuary have not historically supported eelgrass beds or significant eelgrass habitat. Therefore, the threshold analysis for this system is necessarily focused on restoration/protection of infaunal animal habitat.

Overall, the main basin of Hummock Pond is supporting a gradient in impairment from significantly impaired in the upper basin to moderately impaired in the lowest reach near the barrier beach. However, the tributary basin of Head of Hummock is currently supporting severely degraded habitat with no marine invertebrates only 2 species of insect larvae. Head of Hummock contains lower salinity water than the Hummock Pond main basin, likely due to its function as a drown kettle pond in the uppermost reach of the system. As such, Head of Hummock is the focus of groundwater discharge from the watershed and as the entire system is usually without tidal currents, mixing is limited. The salinity of Head of Hummock is low enough (<5 ppt) to influence the plant and animal communities that colonize, although estuarine benthic animal communities are fully capable of colonizing at salinities to 3 ppt. However, the Head of Hummock basin is virtually devoid of benthic animals, only supporting 2 insect larval species and no estuarine infauna. The likely results from the periodic anoxic events during summer in this basin. In contrast, the main basin of Hummock Pond in areas with similar salinities, currently support benthic anaimal communities. Therefore, the loss of benthic animals in Head of Hummock appears to be related to the high organic matter loading and periodic anoxia, rather than the low salinity (as was also observed in Oyster Pond, Falmouth).

The main basin of Hummock Pond is presently supporting significantly impaired benthic animal habitat in its upper reaches as seen by the low numbers of species (4) and individuals (~90), with a moderate to low diversity (1.6). Significantly, stress indicator species (Capitellids, Tubificids) are not prevalent at any station within the main basin, comprising a minor fraction (<2%) of the population. Benthic habitat quality improves moving toward the barrier beach with the lower main basin having moderat numbers of species (8) and individuals (~120) but still moderate to low diversity (1.8). Similarly, the in the basin nearest the barrier beach, habitat is only showing moderate impairment with moderate numbers of species(10) and individuals (~200) and diversity (2.3). Both the values of the habitat indicators and the gradient in quality from upper to lower estuary, are consistent with the observed levels of oxygen depletion (periodic anoxia in Head of Hummock), organic enrichment (chlorophyll a at 40-60 ug L^{-1} in Head of Hummock and <10 ug L^{-1} in the lower main basin of Hummock Pond. The gradient in habitat quality also parallels the TN levels fo 1.6 mg N L^{-1} declining to ~0.7 mg N L^{-1} in the lower main basin. This range in TN has been found to support only impaired benthic animal habitat in open water systems throughout s.e. Massachusetts. Further evidence of impairment of the main basin of Hummock Pond is the dominance of the benthic community by amphipods (*Ampelisca, Leptocheiris*), which are typical of transitional environments (between high and low quality habitat)..

In addition to the watercolum indicators, the lower basin of Hummock Pond has accumulations of macroalgae along the margins of the basin which are associated with poor benthic habitat. Macroalgae can have a "smothering" effect on benthic animals as observed in the most extreme situation of the main basin of Waquoit Bay. The accumulations result in low oxygen at the sediment surface resulting in decline of benthic populations. These accumulations in the lower main basin provide additional stress to benthic communities and are consistent with the observed TN level and observed benthic communities.

The benthic animal communities within the basins of the Hummock Pond System were compared to high quality environments, such as the Outer Basin of Quissett Harbor, which provides additional confirmation of impaired habitat. The Outer Basin of Quissett Harbor supports benthic animal communities with $\geq$28 species, >400 individuals with high diversity (H' $\geq$3.7) and Evenness (E $\geq$0.77). Similarly, outer stations within Lewis Bay in Barnstable currently support similarly high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Eveness (0.74). Equally important these communities are not consistent with nutrient enrichment being composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms (tubificids, capitellids). These habitats represent the highest quality and exist in well flushed basins and have consistently high oxygen and low chlorophyll a levels and low amounts of organic enrichment. While these represent a theoretical goal for restoration, the reality of the tidal flushing characteristics of Hummock Pond must also be taken into account, as with other periodically opened estuaries (Edgartown Great Pond, Tisbury Great Pond).

Overall, the pattern of infaunal habitat quality throughout the Hummock Pond Estuary is consistent with measured dissolved oxygen concentration, chlorophyll, nutrients and organic matter enrichment in this system (Table VIII-1). Classification of habitat quality necessarily includes the structure of the specific estuarine basin and its tidal characteristics (continuously or periodically opened to tidal flows). Based upon this analysis it is clear that the upper regions of the estuary, Head of Hummock and upper main basin of Hummock Pond, are severely degraded and significantly impaired, respectively, by nitrogen and organic matter enrichment while the lower main basin is presently supporting moderately impaired benthic animal habitat. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the upper basin (Head of Hummock) >1.0 mg N L^{-1}, a level associated with impoverished and degraded benthic animal habitat in other s.e. Massachusetts estuaries. Benthic communities have been found to be impaired at TN levels lower than found in Hummock Pond, e.g. Falmouth Inner Harbor, 0.58 mg TN L^{-1}, Fiddlers Cove and Rands Harbor, 0.56 mgTN L^{-1} and 0.57 mgTN L^{-1}, respectively. It appears that Hummock Pond is well beyond its threshold TN level to support healthy benthic habitat. As there is no evidence of present or historic eelgrass beds within the Hummock Pond Estuary, management actions should focus on restoration of benthic animal habitat.

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates that will support acceptable habitat quality throughout an estuary and salt pond is to first identify a sentinel location within the embayment and secondly, to determine the nitrogen concentration within the water column at that site which will result in the desired habitat quality. The sentinel location is selected such that the restoration of that one site (or group of sites) 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 (Section VIII.2), the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved (Section VIII.3.

Table VIII-1. Summary of nutrient related habitat quality within the Hummock Pond Estuary, Town of Nantucket, MA, based upon assessments detailed in Section VII. Head of Hummock is a kettle pond opened via a channel to the upper main basin of Hummock Pond. Hummock Pond is periodically opened to tidal flows, but receives salt water in storm overwash of the barrier beach.

Health Indicator	**Hummock Pond Estuarine System**	
	Head of Hummock Basin	**Hummock Pond Main Basin**
Dissolved Oxygen	SI/SD[1]	H/MI[2]
Chlorophyll	SI[3]	SI/MI[4]
Macroalgae	--[5]	SI[6]
Eelgrass	--[7]	--[8]
Infaunal Animals	SD[9]	MI/SI[10]
Overall:	**SD[11]**	**MI/SI[12]**

1- mooring oxygen <3 mg/L 31%, with multiple day anoxic events, daily excursion 3-5 mg/L, but extended oxygen levels about air saturation (10-15 mg/L versus 8 mg/L) consistent with eutrophic conditions. D.O. less than 4 mg/L is stressful to estuarine organisms. Sediments anoxic-sulfidic mud.
2- mooring oxygen: moderate daily excursions in oxygen levels in upper and lower reach of main basin, generally ranging from 6 mg/L to 8 mg/L, rarely to 5 mg/L; <6mg/L 6% and 5% of record respectively.
3- levels moderate/high, mooring average 34 ug L^{-1}, >25ug L^{-1} 85% of record; blooms >60 ug L^{-1}; WQMP: high chlorophyll a, summer averages of 20-30 ug L^{-1}, averages >10 indicate N enrichment
4- levels moderate/high, in upper main basin mooring average 33 ug L^{-1}, >25ug L^{-1} 75% of record; strong gradient to lower main basin where mooring average was only 8 ug L^{-1}, and >10 ug L^{-1} for 16% or record. Possibility of Head of Hummock influencing upper main Hummock Pond basin. WQMP: shows similar gradient of high chlorophyll a upper main basin declining to 9 ug L-1 in lower main basin.
5- drift algae generally absent, some areas of brackish water macrophytes in shallow margins, sediments of basin are black anoxic sulfidic unconsolidated muds, highly enriched with organic matter.
6- drift algae generally not observed in upper half of basin, but consistently in shallow margins of lower half of main basin; oxidized surface to sediments, and varying levels of medium to fine sand.
7- artificial brackish water basin, no historical evidence of eelgrass beds
8- periodically breached basin, no historical evidence of eelgrass beds, but possibly few sparse patches
9- low numbers of species (2), individuals (<100) diversity and Evenness. Appears that salinity and freshwater inflow areas have shifted bottom community toward freshwater community.
10- sparse stress indicator species, but generally dominated by intermediate organic enrichment species, amphipods (*Ampelisca, Leptocheiris*). Clear gradient: upper HP main basin→mid→barrier beach: increasing # species (4,8,10), numbers (~100 -> ~200), diversity (1.6 -> 2.3) and moderate to good Evenness. Near inlet mollusks, crustaceans, polychaetes, but at levels lower than high quality areas.
11- Severely degraded benthic animal habitat, present community indicative of brackish highly stressed habitat, consistent with periodic anoxia & frequent hypoxia & high phytoplankton biomass (>30 ug L^{-1}). Low species and organism numbers and anoxic sulfidic fluid muds indicative of unstable organic enriched system.
12- Moderately impaired to significantly impaired benthic animal habitat, upper and lower reaches, respectively; community indicates gradient in impairment from the uppermost to the lowermost basin which mirrors the gradient in chlorophyll a and TN. Oxygen conditions generally show little to modest depletion, generally to 5-6 mg/L. Benthic community dominated by amphipods indicative of a system impaired by nitrogen and organic matter enrichment, few stress indicators (capitellids, tubificids).

H = High quality habitat conditions; MI = Moderate Impairment; SI = Significant Impairment;
SD = Severely Degraded; -- = not applicable to this estuarine reach
WQMP: Water Quality Monitoring Program

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Hummock Pond Estuary is based primarily upon the nutrient and oxygen levels and current benthic community indicators, as there is no history of eelgrass colonization of the 2 major basins. Given the information on a variety of key habitat characteristics, it is possible to develop a site-specific threshold, which is a refinement upon more generalized threshold analyses frequently employed.

The Hummock Pond Estuary presently shows a moderate to significant impairment of its benthic animal habitat in its main basin and severely degraded habitat in Head of Hummock and is clearly beyond its nitrogen threshold (i.e. the level of nitrogen a system can tolerate without impairment). The indications of impairment to infaunal animal habitat are supported by the observed levels of oxygen depletion and clearly enhanced chlorophyll a levels, sediment organic matter enrichment and macroalgal accumulations, are similar to other estuaries with similar levels of nitrogen enrichment.

A Sentinel station was established for the Hummock Pond Estuary for development of a nitrogen threshold target that when met will restore benthic animal habitat throughout its estuarine reach. Since there is a relatively small gradient in nitrogen in the main basin, the sentinel station was selected at the basin's mid point, which reflects the average conditions within Hummock Pond. The uppermost station was not selected as it appears to be effected by outflows from Head of Hummock and not reflective of typical conditions within the main basin. Sentinel Station for Head of Hummock was established at the long-term monitoring station 3 (HUM-3). The main basin is typically non-tidal except for 2 brief periods per year, so the main basin supports only a modest gradient in nitrogen. The average total nitrogen levels at the sentinel station are currently 0.72 mg N L^{-1}. It should be noted that the freshening of Head of Hummock must be managed as part of restoration of benthic animal habitat in this estuary. This TN level is comparable to other estuarine basins throughout the region that show similar levels of oxygen depletion, organic enrichment and moderately impaired benthic animal habitat. TN levels >0.70 mg N L-1 are generally characterized as having significantly impaired benthic habitat, phytoplankton blooms and periodic hypoxia and even fish kills (e.g. finger ponds in Falmouth). Benthic animal habitat is typically impaired even at TN levels of 0.58 mg TN L^{-1} (Falmouth Inner Harbor), 0.56 mgTN L^{-1} (Fiddlers Cove) and 0.57 mgTN L^{-1} (Rands Harbor). Given that in numerous estuaries it has been empirically previously determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat (Eel Pond, Parkers River, upper Bass River, upper Great Pond, upper Three Bays, as well as the 7 inner basins of Pleasant Bay) this level is deemed most appropriate for restoration of benthic animal habitat within Hummock Pond. Watershed management to meet the restoration threshold for benthic animal habitat is the focus of the nitrogen management threshold analysis (Section VIII.3).

VIII.3 DEVELOPMENT OF TARGET NITROGEN LOADS

After developing the dispersion-mass balance model of Hummock 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.

With a goal of seeking further improvements in water quality conditions in the Pond, an alternate management scheme was modeled using the previously developed dispersion-mass balance model. The main goal of this proposed management scenario is to prevent time averaged pond-wide TN concentrations in the pond from rising above 0.50 mg/L in the main basin of the Pond (at monitoring station HUM-3) during the summer months, when benthic regeneration and algae production is greatest. A way to achieve these goals is to reduce the watershed loading to the pond, together with an additional mid-summer breach.

Watershed loading was reduced from present conditions until the time averaged TN concentration at station HUM-3 would remain below 0.50 mg/L during a complete breaching cycle, where the pond is open to tidal flushing for at least four days and subsequently closed for 60 days.

The resulting threshold septic loading is presented in Table VIII-1. A 82% reduction from present conditions together with a functioning breach duration of 4 days was required in the septic load to the pond to achieve the threshold requirements. In this scenario 80% of the septic load is removed from the main watershed of the pond, and 95% was removed from the smaller Head of Hummock sub-watershed.

This septic load change results in a 63% change in the total watershed load to the pond, as shown in Table VIII-2. A tabulation of all the loads to the pond is provided in Table VIII-3. The benthic loading term is effected by the change in watershed load. The method described in section VI.2.5.1 was used to adjust the benthic regeneration load to the pond for threshold conditions.

Table VIII-2. Comparison of sub-embayment septic loads used for modeling of present and modeled threshold loading scenarios of Hummock 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)	threshold (kg/day)	threshold change
Hummock Pond main basin	8.436	1.687	*-80.0%*
Head of Hummock	1.366	0.068	*-95.0%*
Total	9.801	1.755	*-82.1%*

Table VIII-3. Comparison of sub-embayment watershed loads used for modeling of present and modeled threshold loading scenarios of Hummock 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)	threshold (kg/day)	threshold change
Hummock Pond main basin	11.195	4.446	*-60.3%*
Head of Hummock	1.682	0.383	*-77.2%*
Total	12.877	4.829	*-62.5%*

Table VIII-4. Sub-embayment and surface water loads used for total nitrogen modeling of threshold conditions for Hummock Pond, 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)
Hummock Pond main basin	4.446	1.918	0.109
Head of Hummock	0.383	0.208	0.473
Total	4.829	2.126	0.582

The effect on TN concentrations through the course of the summer of the threshold management scenario suggested for Hummock Pond is presented in Figure VIII-1. For the 64-day period shown in Figure VIII-1, the time averaged TN concentration is 0.50 mg/L at the HUM-3 monitoring.

It is important to note that the threshold scenario provided as part of this report is one of many possible loading and breaching combinations that could work to improve water quality in the Pond. If the inlet remained open for a period longer than 4 days, the threshold concentration could likely be achieved with less watershed load reduction.

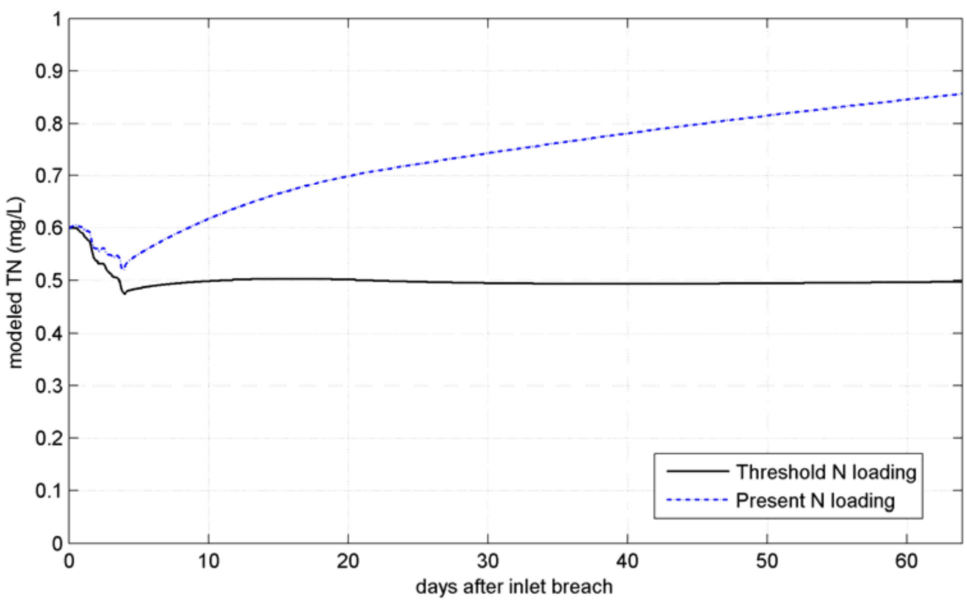

Figure VIII-1. Time series of modeled TN concentrations at monitoring station TGP 7 from the threshold model scenario where the pond is breached in late May for four days.

IX.1 FRESH WATER HEAD OF HUMMOCK

In reviewing historic maps and examining the topography around Head of Hummock, it appears likely that this small brackish kettle pond was artificially connected to the Main Basin of Hummock Pond. The appearance is that Head of Hummock was once fresh water and with the channel and subsequent actions, the pond is now brackish, although consistently less saline than the main basin of Hummock Pond. Head of Hummock remains moderately isolated from Hummock Pond, with outflow of freshwater and some salt water inflows, such as due to storm events. Head of Hummock, as a kettle pond, is deeper than the outer basins (>3 m versus generally 1-2 m). It is highly nitrogen enriched and its sediments reflect its depth and depositional nature, being black fluid muds, which are anoxic and sulfidic and devoid of benthic animals with net nitrogen release to the overlying waters, seen in many kettle ponds opened to salt water inputs (Oyster Pond, Falmouth, Areys Pond, Orleans).

At present, Head of Hummock is a brackish estuarine basin whose nutrient related water quality and habitat quality is dominated by nitrogen availability. This is typical of estuarine systems throughout the region. However, as it appears that this kettle pond was artificially connected to Hummock Pond and now allows input of salt, as part of the MEP restoration analysis, a preliminary analysis of restoring freshwater conditions was undertaken. The concept is that freshwater systems are biogeochemically structured such that phosphorus is the nutrient of management concern and there are multiple “in pond” phosphorus controls available should phosphorus levels result in eutrophic conditions. More important, freshwater systems remove nitrogen that passes through them, lowering nitrogen loads to downgradient estuarine basins. Therefore, the management alternative to be evaluated is to isolate Head of Hummock from Hummock Pond, allowing freshwater outflow for pond level control and fish passage (should it become necessary). This restoration of freshwater conditions would allow Head of Hummock restoration as a freshwater pond, and would provide a reduction in nitrogen load to the main basin of Hummock Pond as part of its restoration of water quality and habitat.

To quantify the possible water quality benefits that would result from returning Head of Hummock to a fresh water pond, a model scenario was developed by modifying the grid developed for existing conditions. Though Head of Hummock is removed from the tidal reach of the system, its watershed would continue to be a nitrogen source to the main basin of Hummock Pond, but with some additional removal by the now freshwater pond. The amount of load that passes to Hummock Pond is controlled by the attenuating capacity of the modified fresh water basin. Based on TN attenuation observed in freshwater ponds with similar depths and retention times throughout the region, it is estimated that Head of Hummock would be able to attenuate 50% of the TN load entering the pond from its watershed. At present, Head of Hummock as a brackish water basin transforms significant amounts of nitrogen but ultimately passes nitrogen to the downgradient main basin.

The changes that result from this modification are large enough to cause noticeable improvements throughout the main basin of Hummock Pond, particularly in how it flushes and how TN concentrations increase during periods when tidal exchange is closed off. However, these changes are not large enough to fully restore the habitat quality of Hummock Pond. The flushing rate of the entirety of Hummock Pond decreases from 4.2 to 3.5 days, an improvement of 17%. The average TN concentration over the entire 64-day simulation period (Figure IX-1) decreases by 0.04 mg/L, which represents an 8% decrease (over open ocean background concentration).

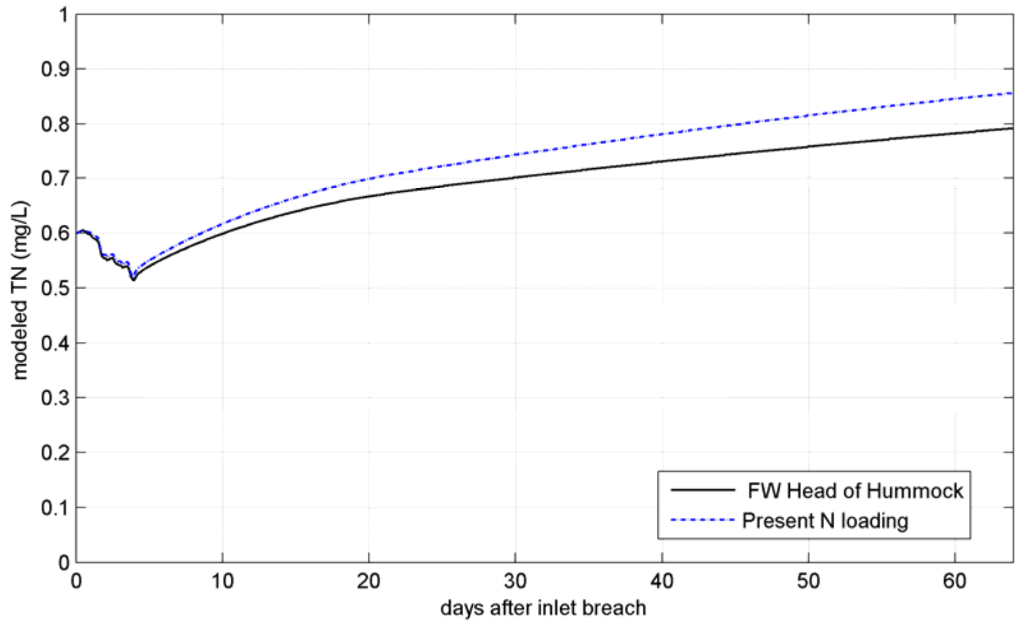

Figure IX-1. Modeled TN concentrations in the main basin of Hummock Pond (at monitoring stations HUM-3) after a simulated four-day open breach and its subsequent closure, with an initial concentration of 0.60 mg/L, showing the N attenuation effect of changing Head of Hummock into a fresh water pond, with no other change in watershed loading.

IX.2 FRESH WATER HEAD OF HUMMOCK THRESHOLD N LOADING

Although the freshwater Head of Hummock scenario is not enough by itself to achieve the N load reductions required to meet the threshold set for the pond, it is possible that it could be used together with additional watershed N load reductions. The N load reduction needed to meet the threshold would be less than the scenario provided in Chapter VIII since Head of Hummock attenuates 50% of the incoming load as a freshwater pond. In addition, restoring freshwater conditions to Head of Hummock also allows separate restoration of this kettle basin in parallel with the restoration of Hummock Pond.

The N loading scenario developed using the freshwater Head of Hummock is presented in Tables IX-1 and IX-II. The freshwater Head of Hummock scenario requires 7% less reduction in total N load and ~9%reduction in wastewater load to meet the threshold. The plot of model output over the 64-day simulation period is shown in Figure IX-II.

Table IX-1. Comparison of sub-embayment watershed loads used for modeling of present (2003), present 2007, build-out, and no-anthropogenic ("no-load") loading scenarios of Hummock 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)	Threshold Scenario (kg/day)	Threshold Scenario change	FW Head of Hummock (kg/day)	FW Head of Hummock % change
Hummock Pond main basin	11.195	4.446	*-60.3%*	4.868	*-56.5%*
Head of Hummock	1.682	0.383	*-77.2%*	0.840	*-50.0%*
Total	12.877	4.829	*-62.5%*	5.708	*-55.7%*

Table IX-2. Build-out conditions sub-embayment and surface water loads used for total nitrogen modeling of Hummock Pond, 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)
Hummock Pond main basin	4.868	1.918	0.119
Head of Hummock	0.840	0.104	-
Total	5.708	2.022	0.119

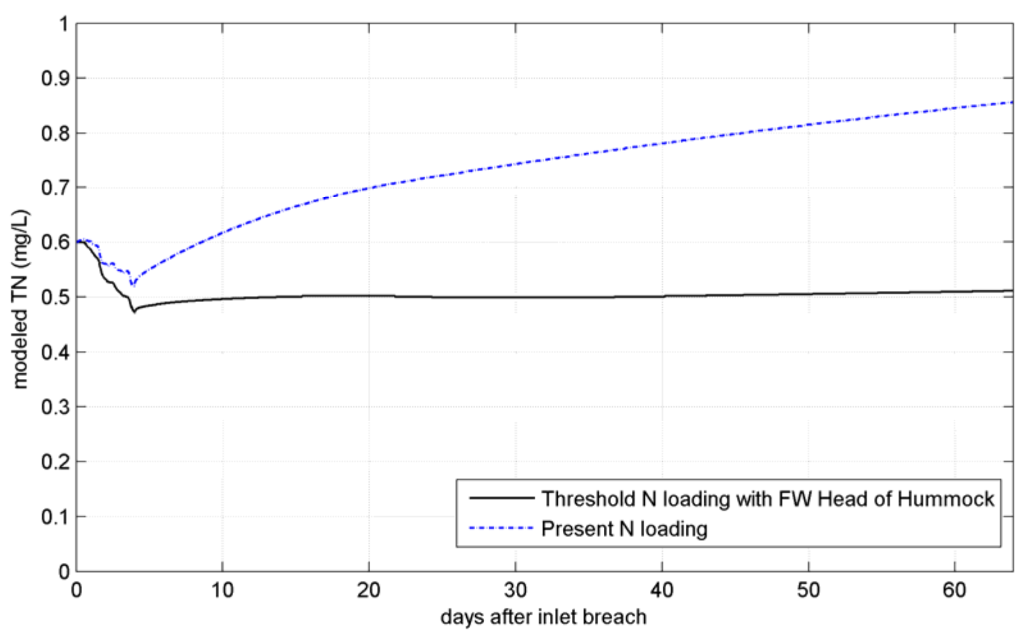

Figure IX-2. Modeled TN concentrations in the main basin of Hummock Pond (at monitoring stations HUM-3) after a simulated four-day open breach and its subsequent closure, with an initial concentration of 0.60 mg/L, for the alternate Threshold N loading scenario that includes the attenuation effect of turning Head of Hummock into a fresh water pond.

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