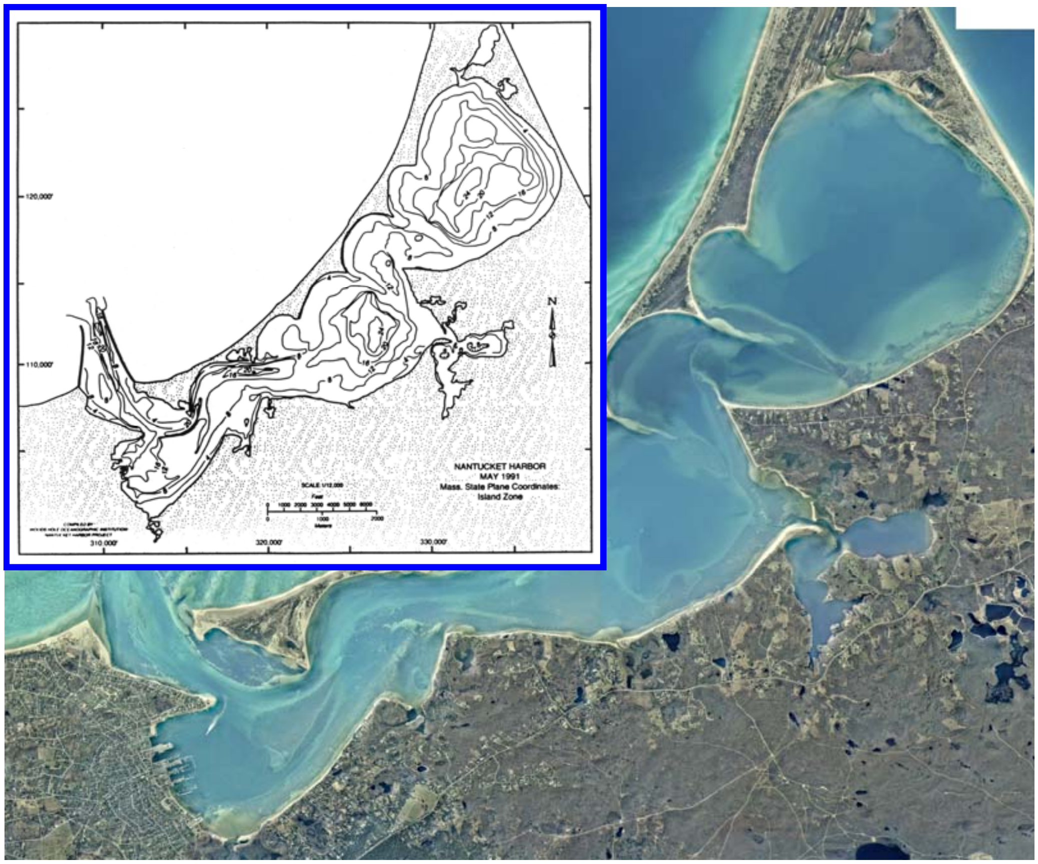
Massachusetts Estuaries Project

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



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of Environmental Protection

FINAL REPORT – NOVEMBER 2006

Massachusetts Estuaries Project

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

FINAL REPORT – NOVEMBER 2006

Brian Howes
Roland Samimy
David Schlezinger

Sean Kelley
John Ramsey

Ed Eichner

Contributors:

US Geological Survey
Don Walters and John Masterson

Applied Coastal Research and Engineering, Inc.
Elizabeth Hunt and Trey Ruthven

Massachusetts Department of Environmental Protection
Charles Costello and Brian Dudley (DEP project manager)

SMAST Coastal Systems Program
Jennifer Antosca, Michael Bartlett and Sara Sampieri

Cape Cod Commission
Xiaotong Wu

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

Massachusetts Department of Environmental Protection

Massachusetts Estuaries Project

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

Executive Summary

1. Background

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Nantucket Harbor embayment system, a coastal embayment of the Island of Nantucket within the Town of Nantucket, Massachusetts. Analyses of the Nantucket Harbor embayment system was performed to assist the Town with up-coming nitrogen management decisions associated with the Towns' current and future wastewater planning efforts, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and harbor maintenance programs. As part of the MEP approach, habitat assessment was conducted on the embayment based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Town of 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 Nantucket Harbor embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Town) for the restoration of the Nantucket Harbor embayment system.

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

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

In particular, the Nantucket Harbor embayment system within the Town of Nantucket is at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater from the increasingly developed watershed to this coastal system. Eutrophication is a process that occurs naturally and gradually over a period of tens or hundreds of years. However, human-related (anthropogenic) sources of nitrogen may be introduced into ecosystems at an accelerated rate that cannot be easily absorbed, resulting in a phenomenon known as cultural eutrophication. In both marine and freshwater systems, cultural eutrophication results in degraded water quality, adverse impacts to ecosystems, and limits on the use of water resources.

The relatively pristine nature of Nantucket's nearshore and Harbor waters has historically been a valuable asset to the island. However, concern over the potential degradation of Harbor water quality began to arise, which resulted in monitoring, scientific investigations and management planning which continues to this day. Nantucket Harbor is one of the largest enclosed bays in southeastern Massachusetts and one of the few with a relatively high water quality capable of supporting significant high quality ecological habitats, such as eelgrass beds, and sustain a scallop fishery. Ironically, it is the pristine nature of this system which may indirectly threaten its ecological health as the coastal waters throughout Southeastern New England become increasingly degraded and the pressure for access and development of remaining high quality environments increases. 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 protection. 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 (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 Nantucket Harbor embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Nantucket Marine Department, with technical guidance from the Coastal Systems Program at SMAST (see Section II). Evaluation of upland nitrogen loading was conducted by the MEP. Estuaries Project staff obtained digital parcel and tax assessors data from the Town of Nantucket Geographic Information Systems Department, watershed specific water use data from the Wannacomet Water Company (WWC) and watershed boundaries adopted by the town as the Harbor Watershed Protection District (http://www.nantucket-ma.gov). During the development of the Nantucket Water Resources Management Plan, an island-wide groundwater mapping project, using many of the USGS wells on the Island, was completed to characterize the water table configuration of Nantucket (Horsley, Whittan, Hegeman, 1990). Estuary watershed delineations completed in areas with relatively transmissive sand and gravel deposits, like most of Cape Cod and the Islands, have shown that watershed boundaries are usually better defined by elevation of the groundwater and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). This approach was used by Horsley, Whittan and Hegeman, Inc. (HWH) to complete a watershed delineation for Nantucket Harbor (Section III); this watershed delineation was been largely confirmed by subsequent water table characterizations (*e.g*., Lurbano, 2001, Gardner and Vogel, 2005). MEP staff compared the HWH Harbor watershed to a 2004 aerial base map. This comparison found some slight discrepancies likely based on a better characterization of the shoreline; changes were made based on best professional judgment and watershed/water table characterization experience in similar geologic settings

The land-use data obtained from the Town was used to determine watershed nitrogen loads within the Nantucket Harbor embayment system and each of the systems sub-embayments as appropriate (current and build-out loads are summarized in Section IV). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Nantucket Harbor 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 Nantucket Sound source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Nantucket Harbor embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the embayments.

MEP Nitrogen Thresholds Analysis: The threshold nitrogen level for an embayment represents the average water column concentration of nitrogen that will support the habitat quality being sought. The water column nitrogen level is ultimately controlled by the watershed nitrogen load and the nitrogen concentration in the inflowing tidal waters (boundary condition). The water column nitrogen concentration is modified by the extent of sediment regeneration. Threshold nitrogen levels for the embayment systems in this study were developed to restore or maintain SA waters or high habitat quality. High habitat quality was defined as supportive of eelgrass and infaunal communities. Dissolved oxygen and chlorophyll a were also considered in the assessment.

The nitrogen thresholds developed in Section VIII-2 were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Nantucket Harbor system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel station chosen for the Nantucket Harbor system. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for protection/restoration of this nitrogen threatened embayment.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Nantucket Harbor 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. The MEP analysis has initially focused upon nitrogen loads from on-site septic systems as a test of the potential for achieving the level of total nitrogen reduction for restoration of the embayment system. The concept was that since septic system nitrogen loads generally represent 28% - 53% of the controllable watershed load to the Nantucket Harbor embayment system and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through this source is a good gauge of the feasibility for protection/restoration of the system.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Nantucket Harbor system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. At present, the Nantucket Harbor System is showing variations in nitrogen enrichment among its 4 principal component basins. The inner basins of Head of the Harbor and Polpis Harbor are nitrogen enriched over Quaise and the Town basins. Although the component basins of the Nantucket Harbor System are clearly enriched in nitrogen over the adjacent Nantucket Sound waters, the enrichment is relatively small, generally <0.100 mg L^{-1} (see Chapter VI).

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). Overall, oxygen within the Harbor bottom waters appears to remain at ecologically healthy levels, except for periodic oxygen depletion within the deepest portions of the Quaise and Wauwinet basins. However, as there were some oxygen depletions below 5 mg L-1 in the main basins (although infrequent), it appears that the system is at or just beyond it ability to assimilate additional nitrogen/organic matter.

Within the highly flushed and generally well mixed waters of the lower basins of Nantucket Harbor, bottom waters were well oxygenated (>6mg L^{-1}). The few excursions below 6 mg L^{-1} were isolated events, rather than a prolonged depletion such as generally associated with a phytoplankton bloom. However, these variations were small and overall the oxygen conditions are consistent with the observations of healthy infaunal and eelgrass communities. While Polpis Harbor also exhibited well oxygenated conditions, larger diurnal variations were recorded than in the outer basins. The higher diurnal fluctuations indicate waters supporting higher phytoplankton biomass. Quaise basin showed both significant diurnal oxygen fluctuations and an overall oxygen decline, although not to levels of high stress. There was a single "event" of a few days when each night oxygen levels reached 4 mg/L, but returned to ~5 mg L^{-1} each following day. Since the meter was located deeper within the basin (~6 m), oxygen levels throughout most of the basin area were almost certainly higher given their shallower depths, only in the "deep hole" was oxygen depletion likely greater. Assessing oxygen conditions within the Quaise basin indicates generally non-stressful oxygen levels, except for the deep basin. However, it is likely that the presence of the deep hole (~30') creates a geomorphological (natural) cause of the low dissolved oxygen. Head of the Harbor showed generally high oxygen levels. As in the Quaise basin, the meter was deeper in the basin and observed oxygen depletions were greater than experienced by bottom waters throughout most of the basin area. The oxygen conditions are consistent with the observed distribution of habitat quality throughout the Harbor System, with the deep waters showing oxygen depletion, but with oxygen levels generally supportive of a high habitat quality for infauna. However, since the system does show oxygen levels less than full atmospheric saturation, additional organic matter loads, (e.g. through nitrogen inputs) will likely increase the magnitude and frequency of the oxygen declines, again indicating a system at or just beyond its nitrogen assimilative capacity (nitrogen threshold)

Based upon all available data it appears that eelgrass is presently a widespread critical habitat within the Nantucket Harbor System. The present distribution of eelgrass results from recolonization of the Harbor from its loss in the 1930's. A map of eelgrass from the 1940's "shows it to be primarily confined to parts of the Jetties and Horse shed at the Harbor entrance (Kelley 1989). Kelley (1989) concluded that from the 1960's to 1989, "eelgrass distribution has been relatively stable in Nantucket Harbor...". However, it is clear that eelgrass beds have been lost from this System. Both the MassDEP analysis and the direct observations of Kelley in 1989 indicated that there has been measurable eelgrass loss. The primary locations are within Head of the Harbor and East Polpis Harbor. The other major region experiencing gradual losses, the marginal areas of Head of the Harbor, is supported by both Kelley (1989) and the MassDEP survey data. This larger areal loss appears to be gradual and occurring primarily in the least well flushed areas of this basin (note the counterclockwise circulation). Eelgrass loss has also been noted to the west of Pocomo, which was observed in the 1980 surveys and more recently in changes from 1995-2001. It is important to note that the eelgrass bed loss is both from the shallow area of the upper and mid regions of Head of the Harbor (<8' depth) and from the "deeper" areas (8'-12') in the lower reach and from the shallow east basin of Polpis. The data indicate that that on the order of 1000 acres of eelgrass habitat within the Nantucket Harbor System is impaired.

It is important to note that the nitrogen levels throughout the Nantucket Harbor System remain relatively low, consistent with the observed oxygen conditions, lack of macroalgae and chlorophyll a levels. However, due to the water depth in the Harbor, it is possible that vertical and horizontal mixing rates appear to have resulted in a decline in eelgrass bed coverage from the deeper areas and more enclosed basin areas.

Macro-algal abundance within the Harbor surveyed in 1994 (Harbor Study 1997) was typical of a relatively healthy environment. Algal cover was highest on the Nantucket Sound side between the points of Coatue (Figure VII-10). The highest concentrations of macro-algae were consistent with the circulation patterns associated with the cusps of land present around the Harbor edge. It also appears that the macro-algal accumulations are not related to terrestrial nitrogen inputs, since the "island" side of the Harbor, which dominates the land based loadings, had lower algal accumulations than Coatue. The absence of macroalgal accumulations and drift algae is consistent with the generally low nitrogen levels throughout this System and the relatively low watershed nitrogen input.

The infaunal data clearly show that the lower basins and shallower areas (<12') of the main Harbor basins generally support high quality infaunal habitat. The lowermost basin (Town) exhibited a dense, highly diverse and relatively evenly distributed community, with some variation. The shallower margins of both Quaise and Head of the Harbor were only slightly less diverse than areas nearer the tidal inlet, but were clearly of high quality. This is further evidenced by the growth of epibenthic scallops in these areas. Within the main Harbor basins, only the deep "holes" showed reduced numbers of species and individuals and organic enrichment indicators. This indication of moderate to poor habitat in these deep regions is consistent with previous analyses and supported by the observed accumulations of organic detritus in these natural depositional areas. It is unlikely that management of nitrogen loading will be able to create significant improvement within these deep basin regions and it is likely that these areas have been "stressed" by natural processes for a long time.

Overall, the MEP system-wide infaunal survey found higher numbers of species and individuals in communities that were generally more diverse and evenly distributed than the other 20 embayments examined to date by the MEP in southeastern Massachusetts. This is consistent with the relatively low tidally averaged nitrogen levels within the system, <0.40 mg N L-1 and generally 0.285-0.361 mg N L^{-1}.

3. Conclusions of the Analysis

The threshold nitrogen level for an embayment represents the average watercolumn concentration of nitrogen that will support the habitat quality being sought. The watercolumn nitrogen level is ultimately controlled by the integration of the watershed nitrogen load, the nitrogen concentration in the inflowing tidal waters (boundary condition) and dilution and flushing via tidal flows. The water column nitrogen concentration is modified by the extent of sediment regeneration and by direct atmospheric deposition.

Threshold nitrogen levels for this embayment system were developed to restore or maintain SA waters or high habitat quality. In this system, high habitat quality was defined as supportive of eelgrass and supportive of diverse benthic animal communities. Dissolved oxygen and chlorophyll *a* were also considered in the assessment.

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Town of Nantucket, Nantucket Harbor embayment system was comprised primarily of runoff from impervious surfaces, fertilizers and wastewater nitrogen. Land-use and wastewater analysis found that generally about 28% - 53% of the controllable watershed nitrogen load to the embayment was from wastewater.

A major finding of the MEP clearly indicates that a single total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of the Great, Green and Bournes Pond Systems, Popponesset Bay System, the Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay, the analysis of the adjacent Rushy Marsh system and the Pleasant Bay and Nantucket Sound embayments associated with the Town of Chatham. This is almost certainly going to be true for the other embayments within the MEP area, as well.

The threshold nitrogen levels for the Nantucket Harbor embayment system in Nantucket were determined as follows:

Nantucket Harbor Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Nantucket Harbor system should reflect both recent pre-degradation habitat quality and be reasonably achievable. Determination of the critical nitrogen threshold for maintaining high quality habitat within the Nantucket Harbor Estuarine System is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. The Nantucket Harbor System is presently supportive of infaunal habitat throughout its main basins, but is clearly impaired by nitrogen enrichment within the Head of the Harbor basin and in the eastern basin of Polpis Harbor, based upon eelgrass losses. Given the documented importance of eelgrass habitat to these basins and the demonstrable loss of eelgrass that were supported, eelgrass restoration in these basins was set as the primary nitrogen management goal for the overall System. Due to the semi-isolated nature of Polpis Harbor from Nantucket Harbor, it is necessary to establish 2 sentinel stations for eelgrass, one in the Head of the Harbor and one in the east basin of Polpis Harbor (e.g. where eelgrass had been observed in 1951-1989).

- It is important to note that the nitrogen levels throughout the Nantucket Harbor System remain relatively low, consistent with the oxygen conditions, lack of macroalgae and chlorophyll a levels. However, the water depth of the Harbor and possibly vertical and horizontal mixing rates appear to have resulted in a decline in eelgrass bed coverage from the deeper areas and more enclosed basin areas. While eelgrass was only recently lost from the east basin of Polpis Harbor, it is presently absent at a tidally average total nitrogen (TN) level of 0.361 mg N L-1. Loss at this nitrogen level is consistent with observed losses in West Falmouth Harbor above 0.350 mg N L-1, however, given the shallower depth of Polpis Harbor, it is likely that it is just slightly above its threshold level at present. Similarly, tidally averaged levels in the lower reach of Head of the Harbor (0.340-0.353) and mid and upper reach (0.390 mg N L-1) also suggest that the recent bed losses are from a recent exceedance of the supportive nitrogen threshold. Given all of the factors discussed above and the similarity of Head of the Harbor to conditions in West Falmouth and Phinneys Harbors and its present nitrogen levels, a nitrogen threshold of 0.350 mg N L-1 was determined to be supportive of eelgrass habitat in this system. This threshold should also support eelgrass in the shallower regions as well. As the east basin of Polpis Harbor has only recently lost its eelgrass and is presently 0.361 mg N L-1, but has shallower waters than Head of the Harbor, only a slight reduction over present levels appears to be needed to support eelgrass habitat. Clearly the threshold must be lower than the present 0.361 mg N L^{-1} and higher than that for Head of the Harbor (0.350 mg N L^{-1}). Therefore, a threshold of 0.355 mg N L-1 was set for the sentinel station in Polpis Harbor. It should be noted that the Polpis Harbor threshold is well constrained by the available data, but is at the limits of the sensitivity of the MEP approach.

It is important to note that the analysis of future nitrogen loading to the Nantucket Harbor 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. Therefore, watershed-estuarine nitrogen management must include management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Nantucket Harbor estuarine system is that protection/restoration will necessitate a reduction in the present (2003) nitrogen inputs and management options to negate additional future nitrogen inputs.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Nantucket Harbor system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Nantucket Harbor system include both upper watershed regions contributing to the major surface water inputs.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
NANTUCKET HARBOR SYSTEM										
Head of the Harbor	0.526	1.152	0.705	0.000	1.858	22.239	-17.211	6.886	0.34-0.41	--
Polpis Harbor	1.836	3.094	0.435	0.000	3.529	2.190	27.441	33.160	0.36-0.39	--
Quaise Basin	0.896	1.731	0.392	0.000	2.123	20.126	43.896	66.145	0.34	--
Town Basin	1.321	10.708	5.194	0.000	15.901	13.888	-2.793	26.997	0.30-0.34	--
Nantucket Harbor System Total	4.578	16.685	6.726	0.000	23.411	58.443	51.333	133.187	**0.30-0.41**	**0.355**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing unattenuated wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings
[5] atmospheric deposition to embayment surface only.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of data collected between 1988 and 2005, ranges show the upper to lower regions (highest-lowest) of a sub-embayment.
[8] Eel grass threshold for sentinel site located at Polpis Harbor.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Nantucket Harbor system. Two threshold scenarios are presented for the Harbor: Scenario A (**N1**) with 100% removal of septic load from the Town watershed together with 80% removal of anthropogenic watershed loads (septic, fertilizer and non-pervious surfaces) from the remaining three Harbor watersheds; and Scenario B (**N2**) with the removal of 100% of septic loads from all four of the Harbor Watersheds.

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
NANTUCKET HARBOR SYSTEM						
Head of the Harbor	1.858	N1: 0.792 N2: 1.153	22.239	N1: -16.795 N2: -17.182	N1: 6.235 N2: 6.210	N1: -57.4% N2: -37.9%
Polpis Harbor	3.529	N1: 2.175 N2: 3.093	2.190	N1: 26.450 N2: 26.655	N1: 30.816 N2: 31.939	N1: -38.4% N2: -12.3%
Quaise Basin	2.123	N1: 1.140 N2: 1.732	20.126	N1: 43.010 N2: 42.885	N1: 64.276 N2: 64.743	N1: -46.3% N2: -18.5%
Town Basin	15.901	N1: 10.707 N2: 10.707	13.888	N1: -2.892 N2: -2.892	N1: 21.702 N2: 21.702	N1: -32.7% N2: -32.7%
Nantucket Harbor System Total	23.411	N1: 14.814 N2: 16.685	58.443	N1: 49.772 N2: 49.466	N1: 123.029 N2: 124.594	N1: -36.7% N2: -28.7%

(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 Nantucket Harbor System. Without these stewards and their efforts, this project would not have been 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, particularly Dave Fronzuto and its Coordinators, past-Tracey Curley and present-Keith Conant. 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. A special thank you is extended to Richard Ray of the Town of Nantucket Health Department for all the assistance provided over the years thus making this report as specific as possible to the Island. In addition, over the years, the Town of Nantucket Shellfish and Marine Department has worked tirelessly with SMAST Coastal Systems Staff, engineers from Applied Coastal Research and Engineering, and the Cape Cod Commission towards the development of a restoration and management strategy for this system over the past decade. 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. A special thanks is given to Linda Holland the prior Director of the Nantucket Land Council who played a key role in promoting scientifically based management of Nantucket Harbor throughout the 1990's.

In addition to local contributions, technical, policy and regulatory support has been freely and graciously provided by Dr. Tony Millham of the Lloyd Center for Environmental Studies who provided previous assessments of the geology and stream discharges. Tom Cambareri and Margo Fenn of the Cape Cod Commission; MaryJo Feurbach, Art Clark and Nora Conlon of the USEPA; and our MADEP colleagues: Andrew Gottlieb (now at ODC), Arleen O'Donnell, Art Screpetis, Rick Dunn, Steve Halterman, and Russ Issacs. We are also thankful for the long hours in the field and laboratory spent by the technical staff (Paul Hendersen, Nat Donkin, George Hampson), interns and students within the Coastal Systems Program at SMAST-UMD. The analysis in this report could not have been performed without data provided courtesy of the authors of the WHOI Nantucket Harbor Study, a forerunner in collaborative scientifically based management of Nantucket Harbor.

Support for this project was provided by the Town of Nantucket (Shellfish and Marine Department), Barnstable County, MADEP, and the USEPA.

This report is dedicated to **Dr. Wes Tiffney** (1938-2003), the long time Director of the UMASS Nantucket Field Station, who was a major supporter of Nantucket Harbor Research for more than 30 years and who provided technical and logistical assistance to researchers gathering much of the data used in this assessment.

SUGGESTED CITATION

Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Nantucket Harbor, Town of Nantucket, Nantucket Island, MA. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The Nantucket Harbor Estuarine System (inclusive of Polpis Harbor) is located within the Town of Nantucket on the Island of Nantucket, Massachusetts. The relatively pristine nature of Nantucket's nearshore and Harbor waters has historically been a valuable asset to the island. However, concern over the potential degradation of Harbor water quality began to arise, which resulted in monitoring, scientific investigations and management planning which continues to this day. Nantucket Harbor is one of the largest enclosed bays in southeastern Massachusetts and one of the few with a relatively high water quality capable of supporting significant high quality ecological habitats, such as eelgrass beds, and sustain a scallop fishery. Ironically, it is the pristine nature of this system which may indirectly threaten its ecological health as the coastal waters throughout Southeastern New England become increasingly degraded and the pressure for access and development of remaining high quality environments increases.

The system has a northern shore (Coatue) bounded by water from Nantucket Sound (Figure I-1). The watershed for this embayment system is distributed entirely within the Town of Nantucket. The potential long-term impacts resulting from the steadily increasing watershed based nutrient inputs, primarily from fertilizers, on-site septic treatment and increased surface runoff associated with increased coastal development has only recently been recognized as a major threat to the health of our coastal waters and that of Nantucket Harbor. Because of the potentially long time lags between nutrient related activity within coastal watersheds and the impacts on coastal waters, significant nutrient related water quality degradation can be initiated before the effects become visible. In the case of Nantucket Harbor, significant in maintaining the water quality within this system is the flushing rate and tidal exchange with the high quality waters of Nantucket Sound.

The morphology, or physical shape of the harbor is the result of three major processes: glaciation, marine erosion and marine deposition. To a large extent Nantucket owes its existence to the late Wisconsin glaciation. At Nantucket the continental ice sheet reached its maximum southern extent about 21,000 years ago. This event is marked by the terminal Nantucket moraine which stretches from Monomoy southeastward towards Sankaty Head (Figure I-2) and can be identified by the typically hilly, hummocky terrain called the Shimmo Hills. Melt water streams issuing from the glacial front deposited sandy outwash plains to the south and southwest of the moraine and which, combined with the slightly younger outwash deposits across western Nantucket, comprise more than two-thirds of Nantucket's surface (Figure I-3).

Within a relatively short period of time after 21,000 yrs B.P., the glacier entered the period of stagnation and retreat. Most of the record of this process has been erased by the erosion of sea level rise and the marine inundation of the Nantucket Sound area, so the following sequence of events is somewhat speculative. The glacial front retreated, first to a line a few kilometers north of the terminal position, and subsequently farther north to Cape Cod (Oldale, 1985). To the north of the moraine in the Shimmo, Quaise, Polpis, Squam Swamp and Quidnet areas are a mixture of outwash, ice-contact and glacial lake-bed deposits laid down during the first of these stagnation-retreat events (Figure I-2; Oldale, 1985). Outwash deposits across the western portion of the island also were deposited at this time. Some isolated remnant blocks of ice were buried in sediments during stagnation/retreat and the subsequent melting of these blocks formed depressions called kettles. The location and bathymetry of Sesachacha Pond suggest it was probably formed this way. Deeper areas of the Head of the Harbor and Quaise may also have been ice block kettles.

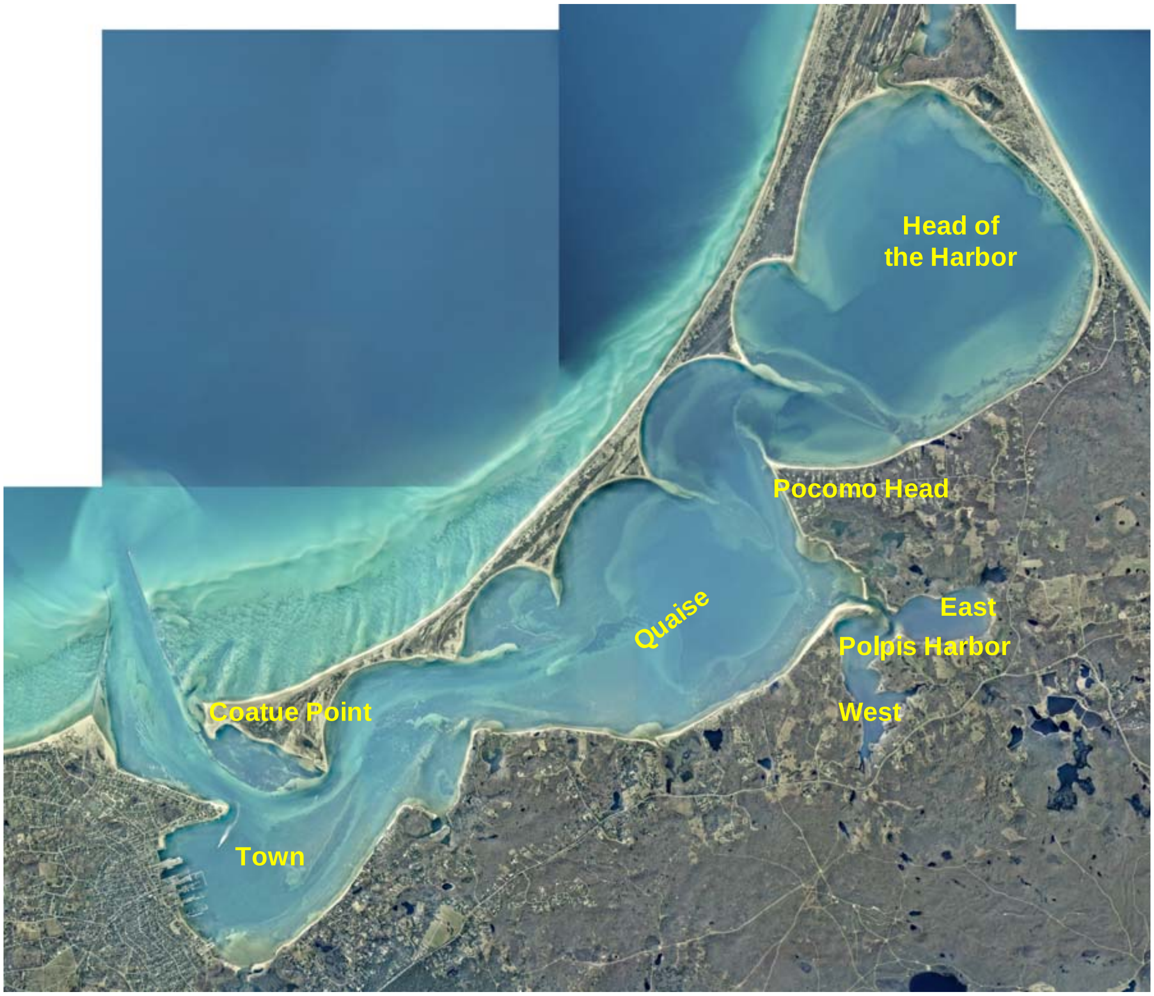


Figure I-1. Major component basins of the Nantucket Harbor Estuary assessed by the Massachusetts Estuaries Project relative to nutrient related habitat health and nitrogen management planning. The Harbor exchanges tidal waters with Nantucket Sound through a single jettied inlet. Freshwaters enter from the watershed primarily through direct groundwater discharge and a series of small, short streams draining wetlands and 1 small surface water discharge (Mill Brook to Polpis Harbor).

The incorporation of large volumes of water in the continental ice sheets lowered sea level by approximately 300 feet, and the resulting shoreline was on the continental shelf about 75 miles south of the current Nantucket southern shore (Oldale, 1995). Following the contraction of the ice sheets, sea level rose rapidly from about 10,000 to 4,000 yr B.P. and thereafter rose more slowly to reach its present level (Oldale and O'Hara, 1980). The marine inundation of the Harbor is constrained by a radiocarbon date of 3,000 yr BP obtained by A.C. Redfield from the base of the 8 foot thick salt marsh peat in Quaise Marsh (W.N. Tiffney, pers. comm.). This date is consistent with older dates obtained from thicker peat deposits by Redfield at Barnstable Marsh on Cape Cod (Redfield and Rubin, 1962). With the arrival of the sea at Nantucket the beach processes of erosion and deposition became the major forces shaping the shoreline of the Harbor for the last few thousand years and continues today.

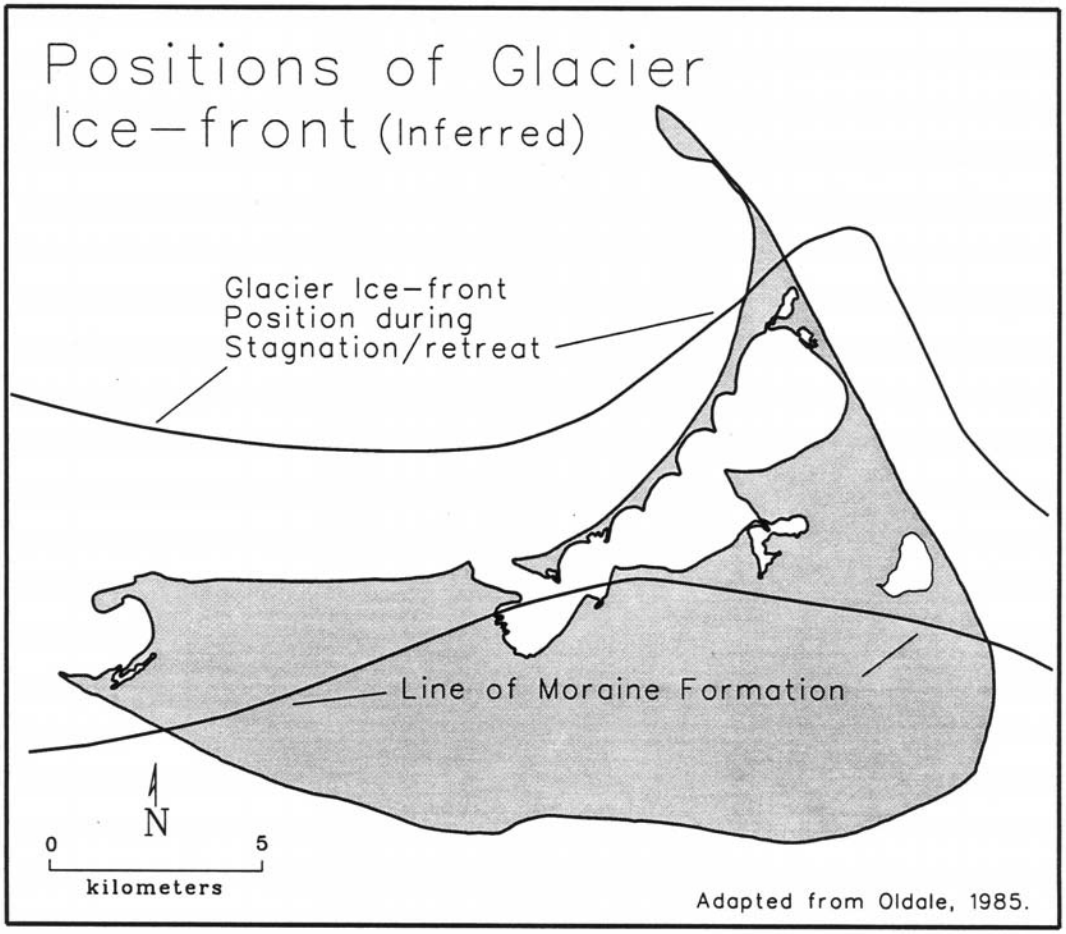


Figure I-2. Simplified map of ice sheet front relative to Nantucket (after Oldale 1985). The southern line indicates a position for the formation of the Nantucket Moraine. A more southerly maximum terminal extension is not shown. The northern stand of the retreating ice sheet was important to the formation of harbor area sediments, moreover there is evidence of glacial lake-bed deposits in Polpis Harbor and a pro-glacial lake in the harbor area.

The sediments which make-up the fabric of the island are unconsolidated and easily eroded by waves, leading to a continuous change in the island's outline. The sediments range from sorted outwash sands to fine clays to gravels associated with moraine deposits. In general, the southern shore of Nantucket has been eroded while the northern shore has been an area of marine deposition. Initially, the Harbor was probably open to the northwest and bounded in the northeast by a tombolo connecting Coskata with the Wauwinet area. The construction of Coatue by beach accretion and spit extension converted what was probably a shallow open bay into the present tidal lagoon with a narrow restricted inlet (Rosen, 1976).

Coatue is entirely formed of beach and dune deposits which have been eroded and transported from elsewhere. The most likely sources for this sediment were deposits in the vicinity of Coskata. The small bluff facing the Head of the Harbor at Coskata is a remnant of more extensive glacial ice-contact deposits associated with the first recessional position of the glacier (Figure I-2; Oldale, 1985). These and surrounding, now eroded deposits to seaward probably formed a sediment supply for the gradual extension of Coatue spit towards the present Harbor mouth (Rosen, 1976).

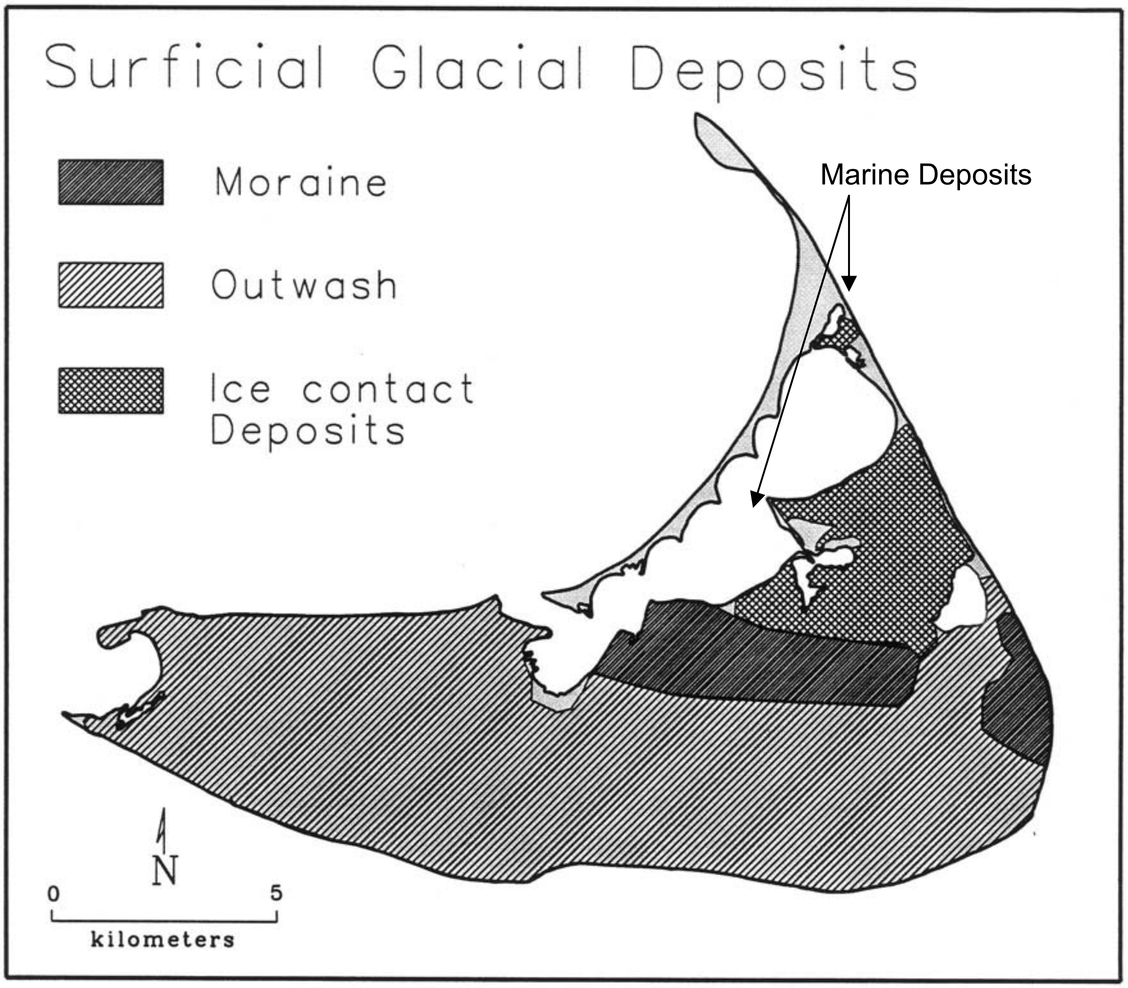


Figure I-3. Generalized distribution of surficial glacial deposits on Nantucket (after Oldale 1985). Extensive deposits of sandy outwash are the result of several depositional events stemming from different ice-front positions. Many of the freshwater and saltwater wetlands in the Polpis Harbor area occur in areas of patchy ice contact (uplands) deposits and fine grained, glacial lake-bed deposits of lower hydraulic conductivity. Coatue and Great Point are marine deposits formed as sea level rose post-glaciation and which are continually being reworked by coastal processes.

In the colonial era the existence of a bar off the mouth of the Harbor and sedimentation of the inlet was a major factor in the economic decline of Nantucket in the mid nineteenth century. The draft of vessels entering and leaving Nantucket was limited by the depth of water over the bar, about 8 feet. As the whaling voyages increased in duration, the size and draft of whaling vessels increased. This limitation of draft and the danger to vessels passing over the bar contributed to the concentration of the whaling industry elsewhere, principally in New Bedford (W.N. Tiffney, pers. comm.).

Major alterations to the Harbor structure have been both natural and human-induced. Management of the harbor circulation was begun as early as the 1930's with the dredging of the inlet (which was ineffective) and continued with the construction of the jetties. Construction of the jetties was begun in the 1880's with the west jetty and ended in 1910 with the completion of the east jetty. A major natural alteration of the harbor geometry occurred as the result of a northeast gale, the "Portland Storm" in 1898 at the site of the Haulover on the Wauwinet-Coskata barrier. A breach was formed that was of limited depth and navigable only by small craft. This second "inlet" maintained itself for about 10 years, during which time it migrated northward about 1 mile before closing (W.N. Tiffney, pers. comm.). Since then, other smaller alterations to the harbor geometry have included maintenance dredging for navigation in the inlet and at Polpis Harbor and dredging between the Head of the Harbor and the central harbor. Natural alterations continue with both gradual sediment erosion and deposition altering tidal flows within individual basins and rapid sediment redistributions resulting from major storms and hurricanes.

The physical setting of the Harbor is a major control of the harbor ecology. The harbor geometry, its area, shape and volume control the circulation and residence time of harbor water. The harbor bathymetry and bottom sediment distribution affect the distribution of some species by limiting their habitat within the harbor. For example, rooted macrophytes like eelgrass are restricted to a bottom depth to which light penetrates. In addition, the geomorphology and surficial geology of the surrounding upland controls the amount and the pathways of freshwater and nutrient delivery to the Harbor. For example, the highly permeable nature of the watershed soils results in only modest surface water inflows, with groundwater being the primary discharge pathway. Perhaps the most significant structural parameter supporting the health of Nantucket Harbor is the relatively small watershed versus estuarine surface area. The result is that the importance watershed nitrogen inputs are generally reduced compared to smaller estuaries, like Green Pond (Falmouth) where the watershed is 20 times the estuarine surface.

The area of the Harbor is about 19.12 km², which includes Coskata Pond, Haulover Pond, the Pocomo Marshes, and Polpis Harbor. The length of the harbor from Nantucket Town to Coskata is 9.7 km and the average width of the harbor is 3.16 km. Mean tide range in the harbor is 0.93m (3.06ft). A detailed marine survey of several thousand depth measurements within the Harbor was conducted in 1991 to determine the bathymetry of the Harbor (Figure I-4). The mid-tide volume is about 6.3×10^7 m^3. The relative distribution of area with depth, or basin hypsometry, is shown in Figure I-5. Mean depth at mid-tide is approximately 8.5 ft (2.6m). The deepest parts of the harbor are in the channels nearest Brant Point and First Point, which are probably maintained by tidal scouring. The deep basins in Quaise and The Head of the Harbor are 10% and 16% shallower than maximum depths at the inlet.

The location of the inlet at the extreme western end of the harbor, the series of six cuspate points on Coatue, and three headland points on the southern shore compartmentalize the Harbor and control the circulation of Harbor water. These compartments or basins form functional units of the Harbor and will be used throughout this report in our characterization of water quality and ecological health of Nantucket Harbor (Figure I-6). The westernmost basin is the Town Basin which is comprised of 2 sub-basins, the Inlet Basin from the base of the jetties to Brant Point and the main Town Basin from Brant Point to a line connecting Second and Abrams Points, which includes the main harbor and mooring areas. The Quaise Basin includes the area from Second Point to a line connecting Pocomo Point with the bight between Five Fingered and Bass Points. Polpis Harbor (East and West sub-basins) is the third basin, while the Head of the Harbor comprises the fourth and largest basin. A breakdown by these four basins of Harbor volumes and areas is shown in Table I-1. The relative areas and volumes of these basins are shown in Figure I-7A and I-7B. Note that the Head of the Harbor basin is nearly half the volume of the whole Nantucket Harbor System and is the greatest distance from the inlet. Similarly, the second largest volume is the Quaise basin and which is the second most distant from the entrance.

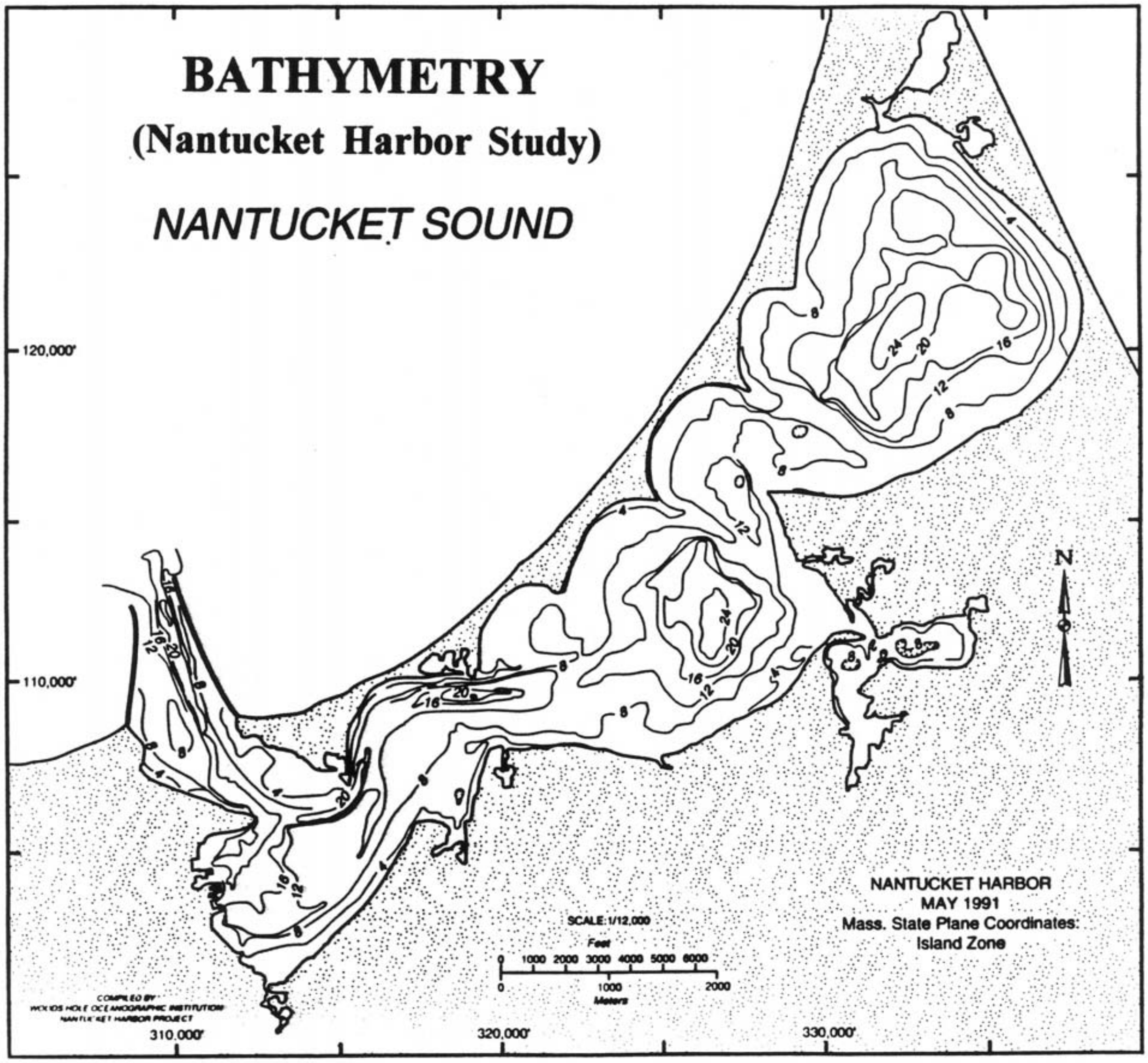


Figure I-4. Nantucket Harbor bathymetric map as determined from surveys conducted in 1990-1991. Contours are in feet.

Unlike many of the embayments on Cape Cod and elsewhere in the MEP study region, Nantucket Harbor supports relatively healthy aquatic habitats associated with its relatively low nitrogen waters. Eelgrass beds within Nantucket Harbor have historically filled most of the seabed throughout the harbor area with the exception of the deeper basin that constitutes a large portion of the Head of the Harbor as can be determined from 1995 and 2001 surveys conducted by MassDEP (MassDEP Eelgrass Mapping Program, Section VII.3) and investigations by the Town of Nantucket (Kelley 1982, 1989). While there has been some evidence of recent gradual declines in coverage, most to the eelgrass beds appear to be stable.

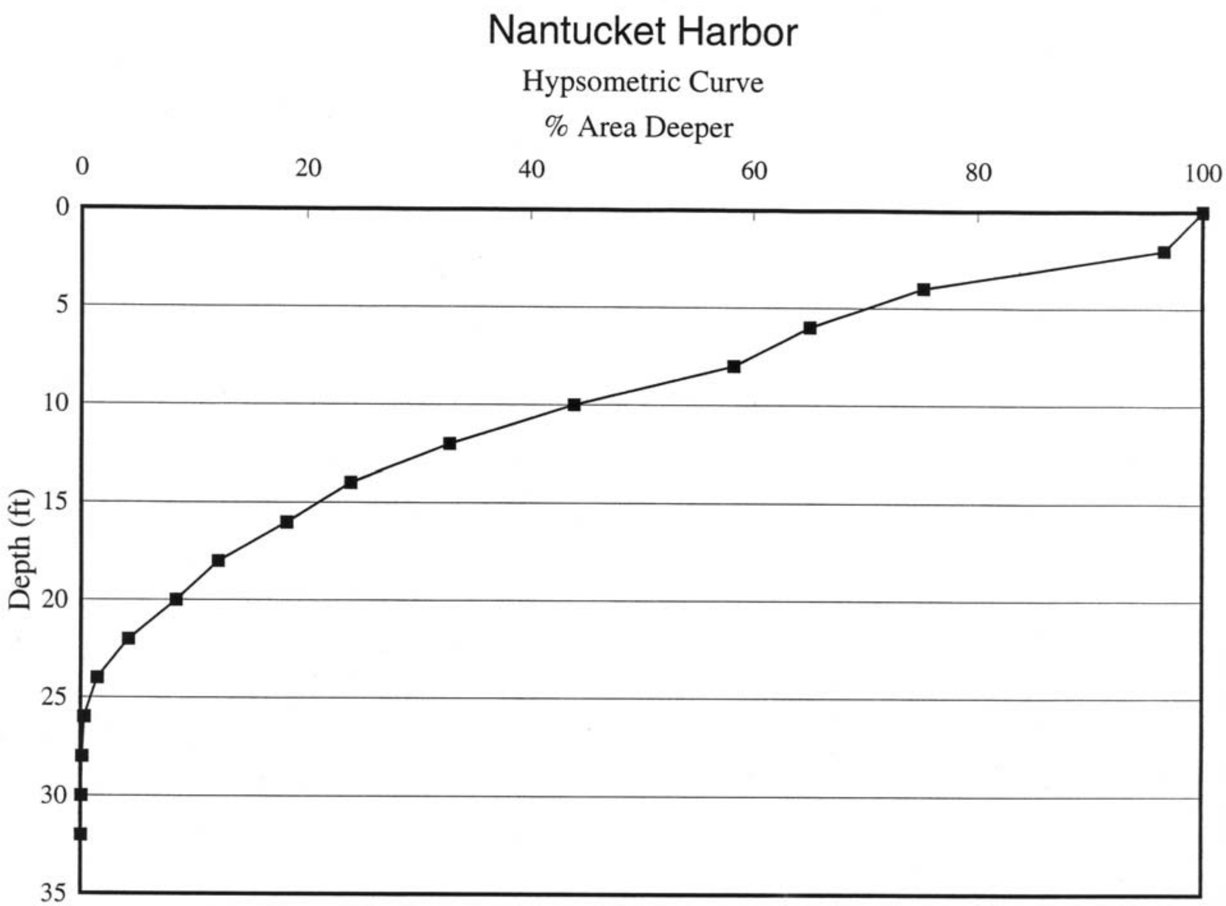


Figure I-5. Hyposmetric curve of Nantucket Harbor based on bathymetry survey conducted in 1990-1991. Nearly 60 percent of the harbor area is less than 10 feet in depth.

The presence of eelgrass is particularly important to the use of Nantucket Harbor as fish and shellfish habitat. The Nantucket Harbor System represents an important shellfish resource to the Town of Nantucket, however, shellfishing activities are suspended by the Massachusetts Division of Marine Fisheries as a result of bacterial contamination from watershed run-off and other potential sources and policy closure of marina areas. The DMF has divided the Nantucket Harbor system into multiple growing areas defined as Nantucket Harbor West (NT2), Nantucket Harbor East (NT3), Polpis Harbor (NT4) and Head of the Harbor (NT5). All four growing areas are classified as approved shellfishing areas with the exception of two sub-areas within NT2 and NT4. The area NT2.2 within growing area NT2 that encompasses the active harbor with boatyards, docks, marina facilities and the ferry terminal has been classified as prohibited to shellfishing as well as area NT4.1 (within the NT4 growing area – Polpis Harbor) located at the terminal end of the southern lobe of Polpis Harbor. These prohibitions result from measured bacterial contamination in these specific areas. Prohibited shellfish growing areas are shown in Figures I-8 and I-9. The Coastal Systems Program at SMAST, has recently completed a bacterial analysis of Nantucket Harbor for the MEP relative to it being on the States 303(d) list. This MEP Report is to provide the scientific basis for the DEP to produce a Total Maximum Daily Load Report (TMDL) as specified under the Clean Water Act. The TMDL focuses on next steps toward the restoration of use of the resource. However, the active harbor area (NT2.2) is closed for regulatory reasons, due to the presence of point source discharges to that area and the fact that it is a boat basin.

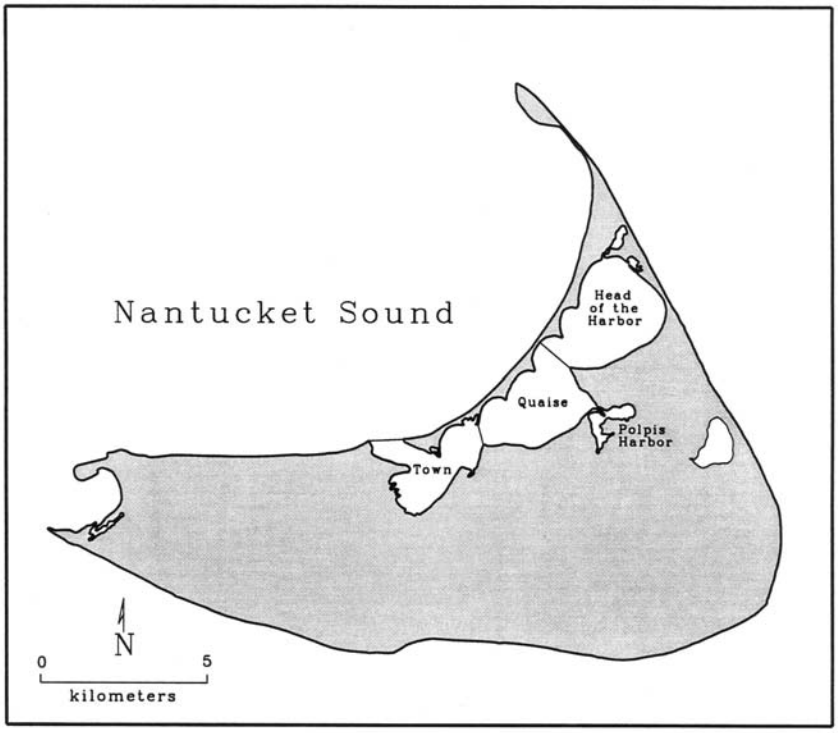


Figure I-6. Map of Nantucket Harbor depicting component sub-basins based on work previously undertaken and presented in 1997 Nantucket Harbor study.

Table I-1. Nantucket Harbor sub-basin morphometry summarizing basin areas and volumes.

Nantucket Harbor Sub–basin Morphometry

Sub–basin	Basin Area (m^2)	Basin Area (ha*)	Basin Volume (m^3)
Head of Harbor	8054370	805	28574356
Quaise	4889764	489	15792271
Polpis	739199	74	1161830
Town	5440905	544	16151094
Total	19124238	1912	61679551

*ha = hectare, 1 ha =10,000 m^2 or 2.471 acres

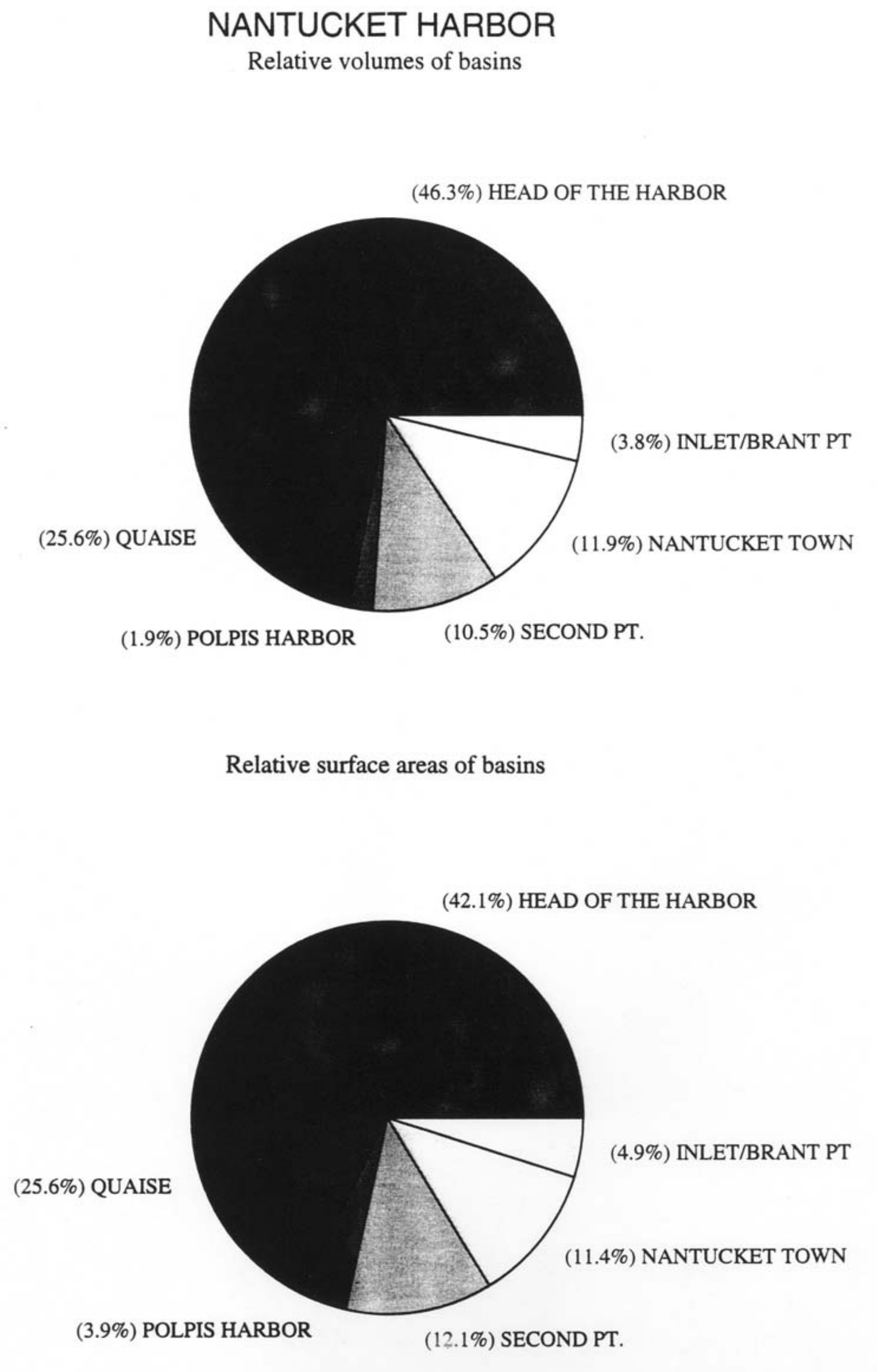


Figure I-7. Nantucket Harbor component sub-basins: A) relative volumes, B) relative surface areas. Head of the Harbor is the largest component sub-basin in the Nantucket Harbor system based on both volume and surface area.

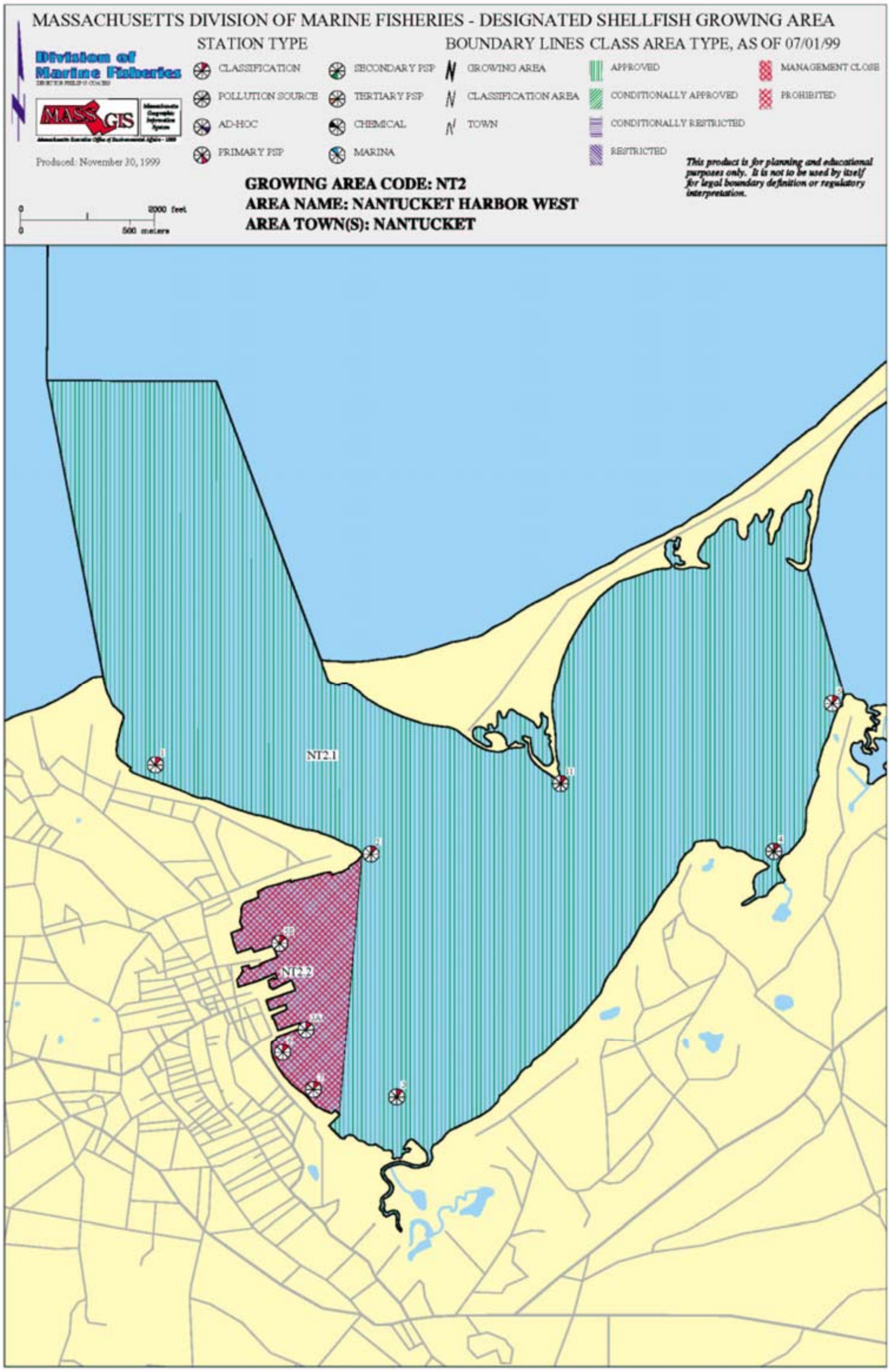


Figure I-8. Massachusetts Division of Marine Fisheries map of designated shellfish growing area NT2 (Nantucket Harbor West) depicting closed area NT2.2.

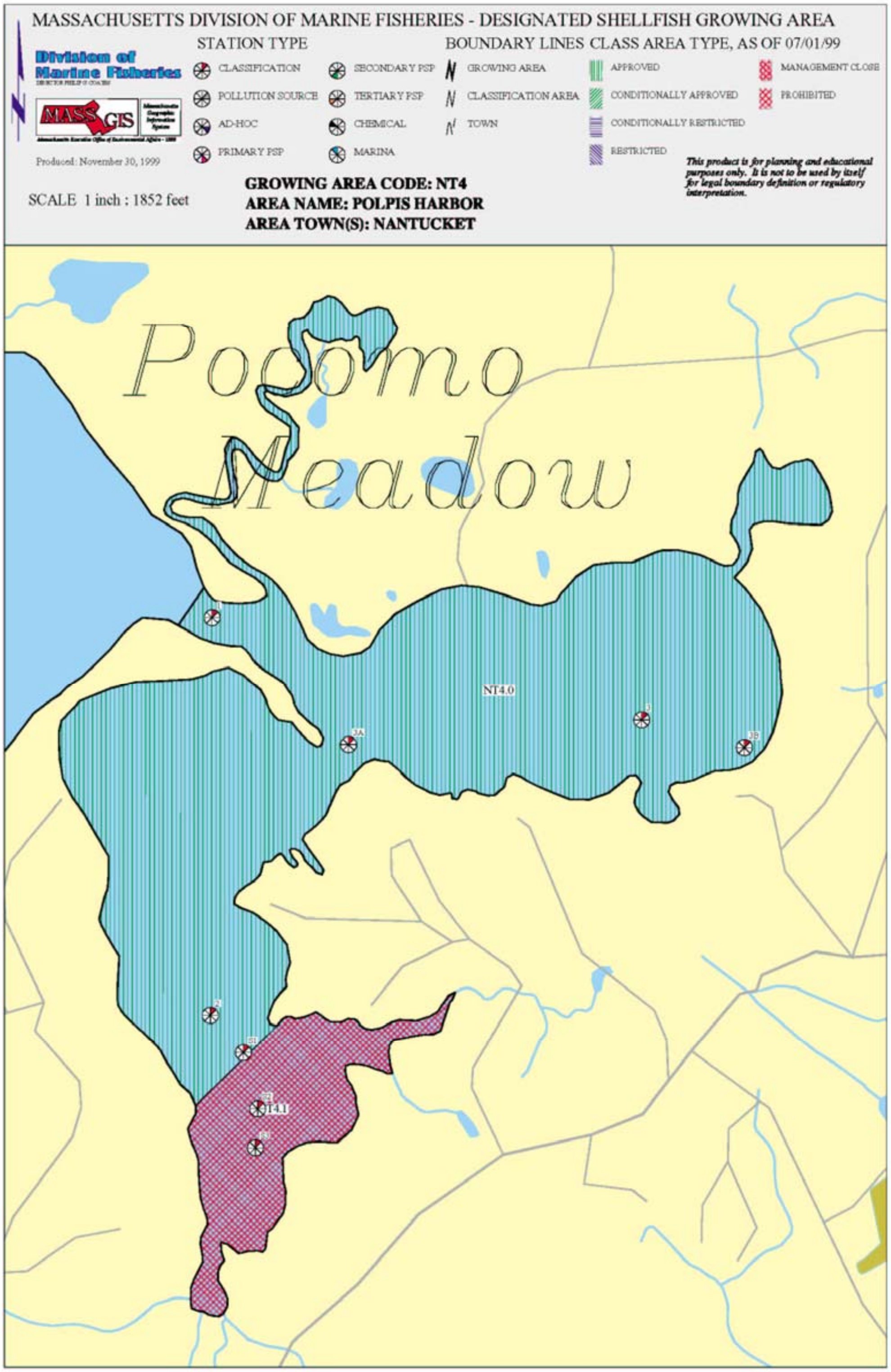


Figure I-9. Massachusetts Division of Marine Fisheries map of designated shellfish growing area NT4 (Polpis Harbor) depicting closed area NT4.1.

Nantucket Harbor is important for recreational boating and supports a wide variety of boating facilities including the ferry terminal, Town Dock, the Winthrop Boat Basin, a boatyard and the Nantucket Yacht Club. As summarized in the 1993 Nantucket Harbors Action Plan, the majority of marina clientele in Nantucket Harbor are large power vessels. Commercial moorings throughout Nantucket Harbor are mostly utilized by sailboats and according to the Nantucket Marine Department, as of the 1993 Action Plan; the summertime weekend turnover rate for boats in the harbor is approximately 100 vessels per day, though that level of traffic may be higher currently. As confirmed by the Nantucket Marine Department, Nantucket Harbor currently supports upgraded pump-out facilities at the Town Dock and Winthrop Boat Basin and the number of boats that can be accommodated at the Town Dock has increased from 56 in 1993 to 100 slips in 2006. The Town Dock supports a sewage pump out station, dinghy docks, public restrooms, potable water and showers, as well as trash and recycling barrels. Similarly, the Winthrop Boat Basin supports dockside pump out stations located on Straight Wharf and Swain's Wharf which also has a fuel dock. Additionally the Winthrop Boat Basin has restroom and shower facilities along with laundry rooms and waste containers for boat slip renters. These waste containers accept oily rags, paint cans, oil filters and other hazardous substances. The Boat Basin also accepts used oil from all boaters in the harbor. Five designated mooring fields exist in Nantucket Harbor and support approximately 1,800 moorings, the vast majority of which are private moorings. In addition to the designated mooring fields, moorings are located in other locations throughout the waters of the Nantucket Harbor system including: an area between the Town Dock and the Boat Basin, within Polpis Harbor (mainly East Basin) and within the Harbor at Wauwinet and Quaise.

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. In particular, Nantucket Harbor, specifically the Head of the Harbor and the Polpis Harbor portions of the overall system, as well as all other embayment systems on Cape Cod, is at risk of habitat impairments from increasing nitrogen loads in the groundwater and runoff from the Harbor watershed.

The primary ecological threat to Nantucket Harbor resources is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters has been increasing over the past several decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to Nantucket Harbor and other Nantucket embayments (Madaket Harbor, Sesachacha Pond, Hummock Pond), like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. The Town of Nantucket has been among the fastest growing towns in the Commonwealth over the past two decades. The Town does have a centralized wastewater treatment facility servicing the downtown area. The construction of this wastewater collection system with its discharge outside of the Harbor's watershed has significantly reduced the nitrogen loading from the watershed development (WHOI Harbor Study 1997). However, there still exist a large number of homes and facilities within the overall watershed to the Harbor that are not tied into a sewer system and therefore rely heavily on septic systems, particularly in the eastern sub-watersheds. These unsewered areas contribute significantly more nitrogen on a per capita basis to the Nantucket Harbor System, both through transport in direct groundwater discharges to estuarine waters and through small surface water flows to the fresh and saltwater marshes that are located along the harbor shore (e.g. Mill Brook discharging to Polpis Harbor).

The Harbor's watershed includes a variety of nutrient sources in addition to residential septic systems, among them the runoff from roads and application of agricultural and lawn fertilizers groundwater discharge of runoff from rooftops and natural areas (grasslands, forest, wetland, etc). Atmospheric deposition on the watershed is accounted for in the various land-use evaluations. The greatest level of development and residential load is situated in the nearshore regions of the system. For the current analysis, estimates of nitrogen loading to the Harbor from the watershed have been conducted by SMAST scientists and the Cape Cod Commission, previous studies for the Town of Nantucket were also incorporated, as appropriate. The bulk of the present watershed nitrogen loading to the Harbor waters is from residential housing and light commercial areas, as well as associated sources (roads, driveways, etc.) that exist within the system watershed.

As noted in previous studies (WHOI Harbor Study 1997, Nantucket Harbor Watershed Work Group 2003), direct atmospheric deposition of nitrogen on the estuarine surface of the Nantucket Harbor System is the dominant source of nitrogen to Harbor waters. The present MEP effort, confirms these previous determinations. The reason for this "atmospheric effect", relates to the size of the estuarine water surface and the estuary's small watershed area and relatively low nitrogen load. Again, the low watershed nitrogen load relates to the removal of wastewater generated in the densely developed portion of the watershed and the relatively low density of development in the eastern subwatershed areas. However, it should be noted that various sources document a gradual decline of estuarine habitat quality within the innermost basins over the past several decades (Head of Harbor, Polpis Harbor).

At present, Nantucket Harbor appears to have reached its nitrogen loading threshold, the level of nitrogen input that a system can tolerate without showing a decline in habitat quality. The clearest evidence of this is the gradual loss of eelgrass within the Head of the Harbor basin and Polpis Harbor (East basin), but its extensive and largely healthy areas of eelgrass beds throughout the western basins. The changes in eelgrass have been confirmed by a number of researchers over the past 2 decades. Consistent with a system at its nitrogen threshold for eelgrass habitat, the bulk of the Harbor is currently supporting healthy benthic animal habitat, critical for supporting the Harbor's and coastal food web (e.g. fish, shellfish, avian fauna, etc).

As the Harbor watershed has not yet reached build-out (i.e. watershed nitrogen inputs will increase), it appears that nitrogen management will be needed to prevent further declines in system health. However, unlike many embayments in southeastern Massachusetts, nitrogen management associated with Nantucket Harbor needs to focus on only modest reductions of present load and controlling future loading.

The Town of Nantucket, as the primary stakeholder to the Nantucket Harbor embayment system, has been concerned over the quality of this significant coastal resource. The Town has supported a number of studies related to the health of the Harbor and created a Nantucket Harbor Watershed Overlay to support management planning. In addition, there has been significant effort related to planning by various groups (e.g. Nantucket Harbor Watershed Work Group, Shellfish Habitat Advisory Board, Nantucket Land Council). The community has worked to implement controls on direct stormwater discharges, which has had positive effects on Harbor bacterial contamination. The Town of Nantucket's Marine Department and Health Departments have focused on this and other Town embayments for protection and restoration. In addition, the Town of Nantucket has supported a long term Water Quality Monitoring Program which has been collecting data on nitrogen related water quality within the Nantucket Harbor System since 1988. The Nantucket Marine Department has collected the principal baseline water quality data necessary for ecological management of the Island’s embayments and harbors. The monitoring program is a town-based water quality monitoring program run by the Marine Department (D. Fronzuto and T. Curley and K. Conant, Project Coordination) with technical and analytical assistance from the staff at the Coastal Systems Program at SMAST-UMD and a contract laboratory.

The common focus of the Nantucket Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments of the Island and determine the relationship between observed water quality and habitat health. The Nantucket Water Quality Monitoring Program effort in Nantucket Harbor developed a data set that elucidated the long-term water quality of this system. Additionally, as remediation plans for various systems are implemented, the continued monitoring will help satisfy monitoring requirements by State regulatory agencies and provide quantitative information to the Town relative to the efficacy of remediation efforts. The MEP effort builds upon the water quality monitoring program, and previous hydrodynamic and water quality analyses conducted by Applied Coastal Research and Engineering and SMAST scientists who were previously researching Nantucket Harbor while in residence at the Woods Hole Oceanographic Institution. The current analysis of the Nantucket Harbor system includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Nantucket Harbor embayment system, and its major sub-embayment (Polpis Harbor).

In conjunction with other Town efforts, the Town of Nantucket Planning and Economic Development Commission, as well as the Nantucket Land Council, continue to enhance their tools for gauging future nutrient effects from changing land-uses. The GIS database used in the present MEP evaluation is part of that continuing effort. Based on the wealth of information obtained over the many years of study of the Nantucket Harbor System, the Harbor embayment system was included in the first round prioritization of the Massachusetts Estuaries Project to provide state-of-the-art analysis and modeling. This effort was undertaken as a partnership between key Town of Nantucket staff and the MEP Technical Team. Additionally, given that the MEP was able to fully integrate the Towns' on-going data collection and previous ecological assessment efforts undertaken in the harbor, primarily from the WHOI Nantucket Harbor Study, **no additional municipal funds were required** for the conduct of MEP assessment and modeling and nitrogen threshold analysis.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master 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. The modeling tools developed as part of this program provide the quantitative information necessary for the Town Nantucket to develop and evaluate the most cost effective nitrogen management alternatives to restore the Town's valuable coastal resources currently being impacted by nitrogen overloading. Further, the MEP Linked Watershed-Embayment Model, now calibrated and validated, can be used to evaluate various management approaches for ecological benefit/cost analysis.

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. At its higher levels, enhanced 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 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 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 newest 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 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 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 implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

In appropriate estuaries (Nantucket Harbor and Sesachacha Pond included), TMDLs for bacterial contamination will also be conducted in concert with the nutrient effort (particularly if there is a 303d listing). However, the goal of the bacterial program is to provide information to guide targeted sampling for specific source identification and remediation. The Coastal Systems Program at SMAST-UMD has completed the draft bacterial technical reports for Nantucket Harbor and Sesachacha Pond and they are currently under review by MassDEP and USEPA.

As stated above, the major focus of the MEP is to develop site specific nitrogen thresholds to support nitrogen management planning. The MEP uses a site specific modeling and analysis approach for the assessment of specific estuaries and to evaluate available management options for meeting selected nitrogen goals, protective of embayment health.

The major Massachusetts Estuaries Project goals are to:

- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment model available to address future regulatory 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 ca. 20 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 suggests "solutions" for the protection or restoration of nutrient related water quality and allows testing of "what if" management scenarios to support evaluation of resulting water quality impact versus cost (i.e., "biggest ecological bang for the buck"). In addition, once a model is fully functional it can be "kept alive" and corrected 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 fully field validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-10). This methodology integrates a variety of field data and models, specifically:

- 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

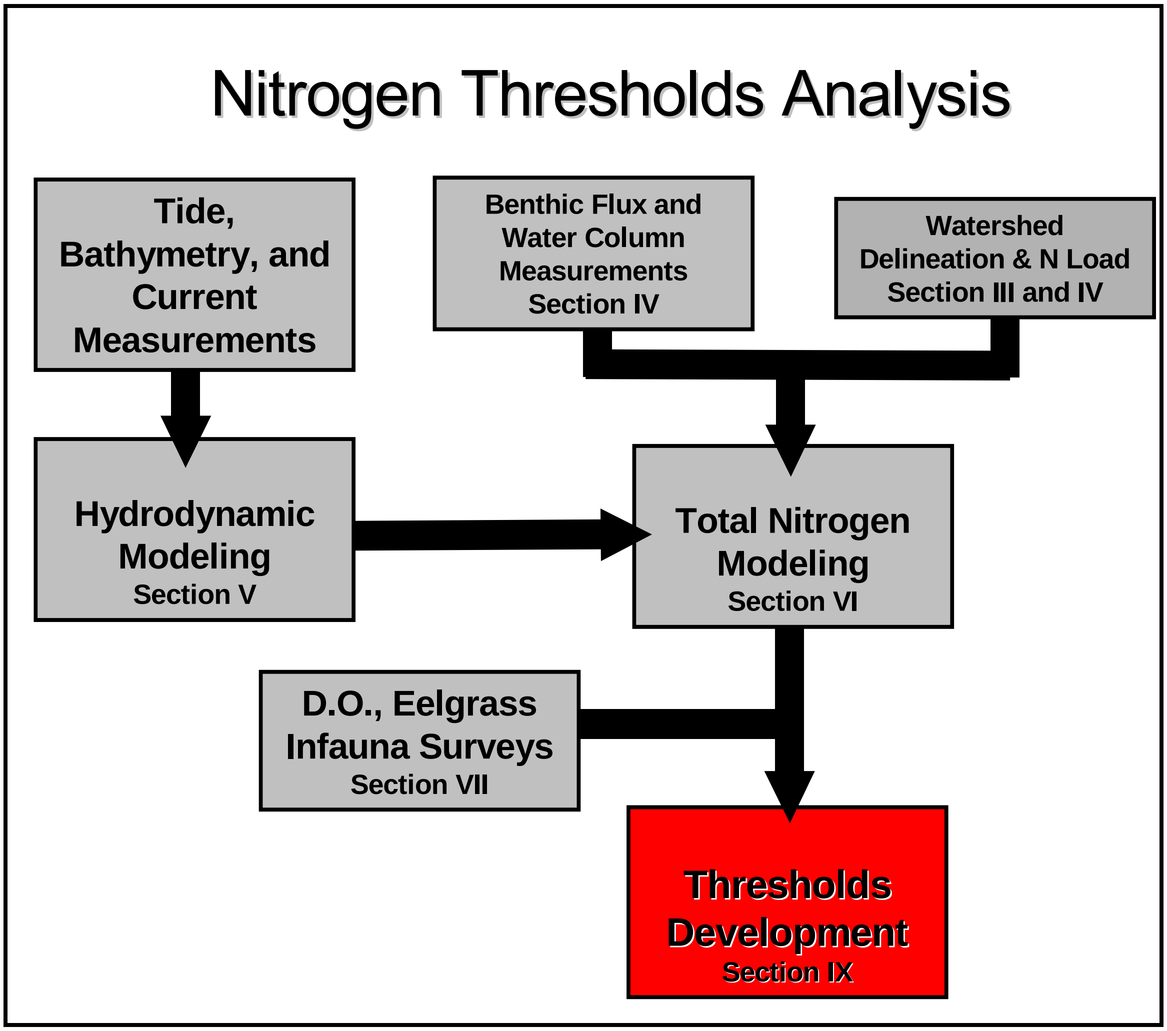


Figure I-10. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

I.2 SITE DESCRIPTION

The Nantucket Harbor System is a complex estuary comprised of a large lagoonal estuary, Nantucket Harbor, with basins running parallel to its watershed and is formed behind a barrier beach (Coatue) and a small drown river estuary (West Polpis basin) receiving surface water inflow and supporting significant salt marsh resources. The Harbor system also contains smaller wetlands (e.g. The Creeks) and salt ponds. The Nantucket Harbor Estuary was formed primarily through the gradual expansion of the barrier beach that is known as Coatue Spit. Nantucket Harbor is an embayment of the greater Nantucket Sound marine system and exchanges tidal waters with the Sound through a single armored inlet. Inlets are by their physical structure generally less well flushed than larger water bodies and are therefore susceptible to negative impacts from nutrient loading. For the Purpose of this analysis the Nantucket Harbor System into five subsystems, each playing different roles, having different flushing rates and with differing sensitivities to nutrient related impacts. The major sub-embayment within the Harbor System, Polpis Harbor, is a smaller water body with direct connection to the Harbor waters. The smaller enclosed nature of the 2 sub-basins to Polpis Harbor can result in reduced rates of tidal flushing making them more susceptible to the potential for low oxygen conditions resulting from either natural or human inputs. Three subsystems represent the main basins of the harbor proper (Town of Nantucket Basin, Quaise and Head of the Harbor), and one subsystem is represented by Nantucket Sound, the source of the low nutrient, oxygenated tidal water for the harbor.

Most of Nantucket Island and the immediate environs are made of sediments derived from primarily crystalline bedrock and reworked by the glacier (Oldale 1985: E-an Zen 1982). Though there are some fine-grained deposits of glacial lake origin, the position of the island at a terminal moraine meant that much of the finer fraction of sediments carried by glacial melt water streams was transported some distance from the area. As sea level rose near Nantucket, marine erosion of the glacial deposits tended to further preferentially winnow fine deposits out of the surficial deposits and transport them seaward to deep water. The sediment source and the marine winnowing are principal reasons for the preponderance of sandy bottom sediments in the Harbor and around the island.

It appears that prior to the extension of Coatue, a large part of the south shore of the Harbor from the Town to Pocomo and perhaps Wauwinet was open to the northwest wind. This more open Harbor was thus exposed to higher wave energy and marine erosion than is currently possible across the present Harbor width. During this period, erosion of the headlands on that shore must have provided material for filling some of the present harbor bottom and the wind and wave energy may have been sufficient to limit deposition of fine-grained material within most of the Harbor, resulting in a sandy bottom. With the extension of Coatue, the harbor environment became more protected and present depositional conditions began. It is under these less turbulent conditions that the present Harbor communities have developed. The shallowing of the harbor and the reduction in wave energy has allowed the development of extensive eelgrass beds (*Zostera marina*). The expansion of the eelgrass further dampens wave energy, increases sediment deposition and creates a stable benthic environment for secondary colonization by benthic infauna and associated fish. Most importantly to the present economy of Nantucket, the extensive eelgrass beds are capable of supporting scallop development, hence an harvestable resource. As eelgrass cannot be found in even the most pristine waters of Buzzards Bay below a depth of 6.5 meters, it is unlikely that eelgrass ever colonized the deep basins of Quaise or Head of the Harbor.

Lidz (1965) sampled harbor sediments for grain size and produced a map of the distribution of sediment grain-size, Figure I-11. The map suggests effects that Harbor morphology and the availability of coarse sediments have on the observed sediment distribution. The majority of the harbor bottom has sediment grain-size larger than 250 microns which is the lower boundary for medium sand diameter. The areas of coarsest sediments, greater than 2000 microns (very fine pebbles) are in the main tidal channels in the inlet and at Second Point and large quantities of shell fragments during Lidz's study. Other sites of coarse bottom sediments greater than 1000 microns, or very coarse sand are Third, Five Fingered, Pocomo and Bass Points. These points are the focus of wave energy generated from the two prevailing wind directions in the harbor (Rosen, 1975).

Also important to assessing the Harbor sub-systems is an evaluation of the organic-rich sediments, because their extent and relative concentration represent a reserve of reduced organic material and nutrients which through the process of sediment respiration constantly recycle nutrients to and withdraw dissolved oxygen from the overlying water. In a previous study, MEP Technical Team members sampled bottom sediments at more than three hundred sites and compiled a map of the distribution of sediment type by percentage of organic matter (Figure I-12), which is roughly correlated with sediment particle diameter (Figure I-11). The principal control of organic matter deposition in the harbor is the level of wave and tidal current energy available to resuspend and transport small-diameter bottom sediments. With the exception of tidal current scoured channels, there is a strong positive relationship between water depth and the percentage organic material in the sediment. The depth at which waves will resuspend bottom sediment is to a large extent limited by the height of the wave. Wave height is a function of wind strength and wind fetch or the horizontal distance over the water surface which waves can propagate. As wave height increases the depth to which sediments will be resuspend from the bottom increases. Along the shore and in shallow water fine sediment particles can be resuspended during average wind and wave conditions. The influence of larger waves generated by higher winds reaches correspondingly deeper parts of the bottom. The maximum depth of wave resuspension in the harbor seems to be about 12 feet below mid-tide, and is demonstrated by the pattern of organic carbon in the Head of the Harbor, where deposition of carbon greater than 1% by weight corresponds to the 12 foot depth. Per cent carbon greater than 3% is limited to depths below 16 ft. The 12 foot contour also agrees fairly well with the distribution of eelgrass beds throughout the Harbor System.

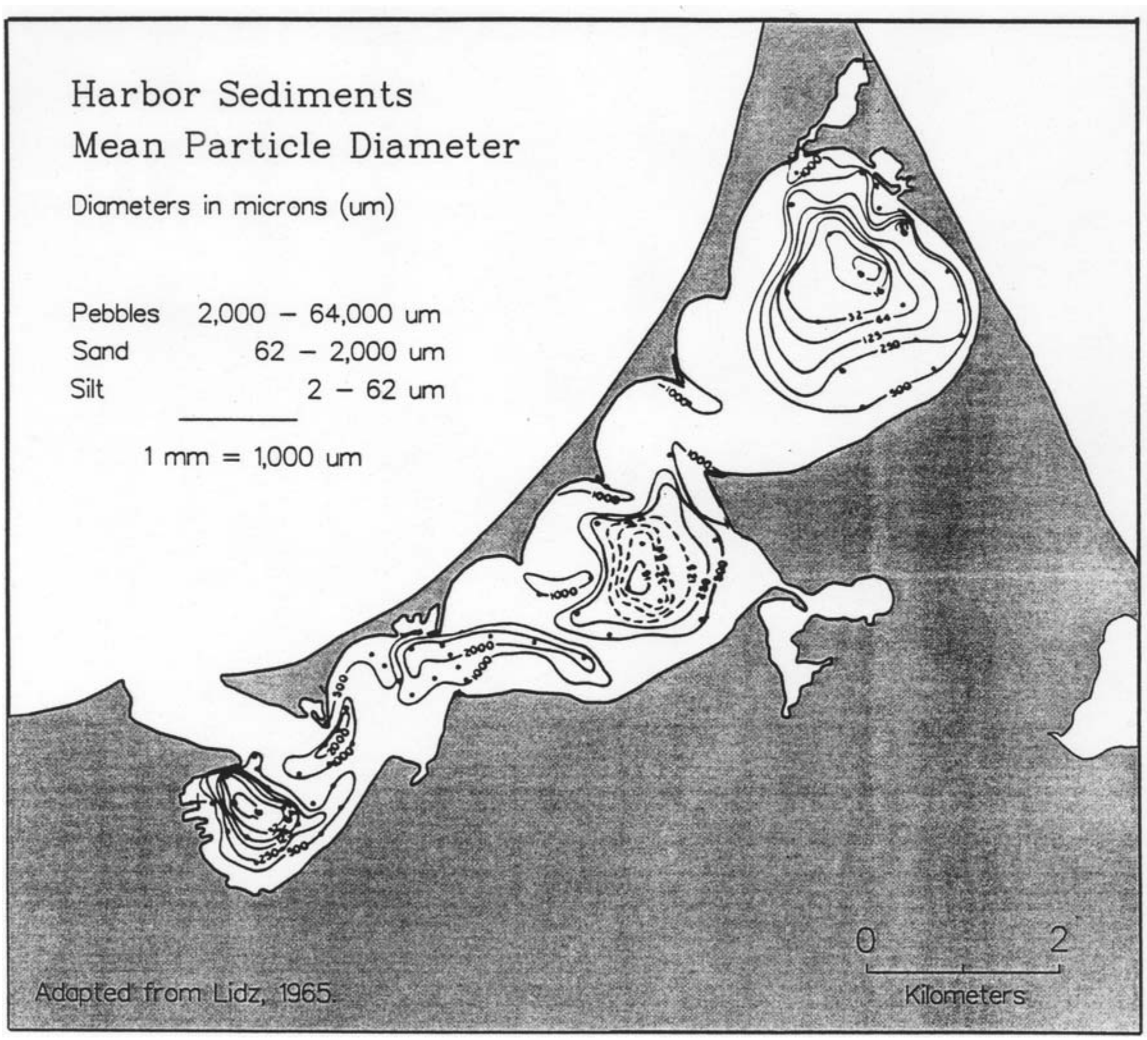


Figure I-11. Sediment distribution by grain size in Nantucket Harbor (after Lidz, 1965).

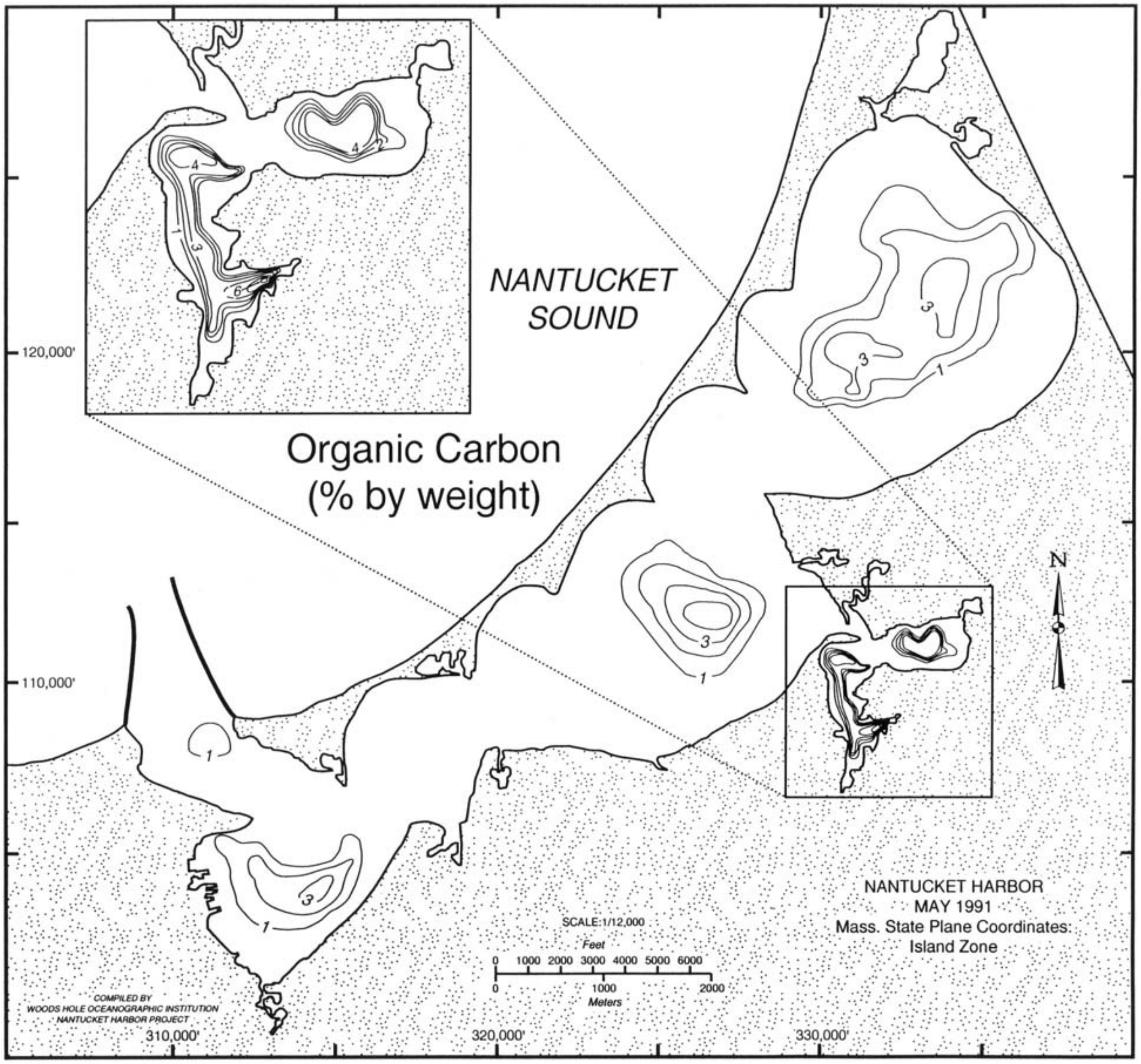


Figure I-12. Distribution of sediment organic carbon in Nantucket Harbor as determined from >300 samples collected throughout Nantucket Harbor (courtesy D. Schlezinger and B. Howes).

The second control on organic deposition is the occurrence and strength of tidal currents. Where current velocities are sufficiently high suspended sediments in the water column will not settle. Higher current velocities will begin to re-suspend bottom sediments, winnowing out successively larger sediment particles as the velocity increases. Bridle and Tracey (1949) demonstrated that tidal currents in the Head of the Harbor Basin were important only near Bass Point, and were very weak further into the basin. Because current velocities are very low in the Head of the Harbor organic deposition in this basin is probably principally controlled by wind and the water depth.

Organic carbon distribution in the Quaise basin reflects the operation of both physical controls. Organic deposition occurs in the main deep basin in a pattern similar to the Head of the Harbor. However, there are two deeps associated with tidal currents off Third Point and west of Pocomo Point which are not sites of organic deposition due to tidal current scouring. The highest organic matter levels for the whole Harbor were measured in Polpis Harbor. Polpis Harbor is well protected from waves generated in the Quaise basin and also protected from all wind directions, so it acts as a sediment sink. Areas near Polpis inlet show low organic concentrations due to tidal scouring. The net effect of physical processes on sediment deposition has been to concentrate organic matter in the deeper basins which are most likely to stratify or in Polpis Harbor which has high terrestrial loadings. The effect is to produce conditions of high sediment oxygen demand in just those areas most susceptible to developing low oxygen conditions.

The other principal site of organic deposition is in the Town basin, where organic deposition is less strongly correlated with depth. The highest concentration of organic carbon occurs partly over Hussey's Shoal where depths are less than 4 feet at mid-tide. Control of organic-rich sediment deposition in the town basin is likely due to several factors: reduced tidal velocities; being in an eddy area off the main Harbor tidal channel; and during the periods of high water column productivity, being in the lee of the prevailing southwest summer winds.

Other factors have contributed to high organic levels in the Harbor basin also. Historically the Town Basin received direct input of organic wastes from public and domestic sanitary sewers, from street runoff, and from recreational and commercial vessels in the harbor. Most of these sources have been eliminated over the past 40 years, but the organic sediments which built up from these long-term inputs take time to be broken down. A survey of organic carbon in the harbor was conducted in 1965 by Lidz (Figure I-13) which shows generally higher organic carbon in the western portion of the Harbor which is not reflected in our survey, and which Lidz concluded was due to the high organic inputs from Nantucket Town. The validity of the contention that Town Basin sediment organic matter levels may be declining is at present uncertain since different methods employed in the 1965 and 1991 surveys. However, it is clear that the general pattern of organic carbon deposition has not changed over past 40 years as would be expected given the stability of the overriding physical factors and the relatively low terrestrial loading to the Harbor.

Differences in physical processes within the Harbor components are a primary cause of the differences in sediment characteristics and nutrient tolerances of the various basins. In general, the deeper basins with their higher organic deposition rates and tendency to vertically stratify are the most susceptible to habitat degradation under increased nutrient loadings. Unfortunately, the deepest basins are also farthest from the source of high quality Nantucket Sound water which amplifies their potential for problems. Smaller more heavily loaded basins, such as Polpis Harbor, also are susceptible to organic matter derived low oxygen problems, since they tend to receive large organic matter inputs (or disturbances). The physical structure of the Harbor helps to control the water circulation, wave energy and vertical mixing and organic matter deposition. These features plus secondary effects on oxygen consumption and resupply play major roles in determining the susceptibility of Nantucket Harbor to nutrient related water quality decline.

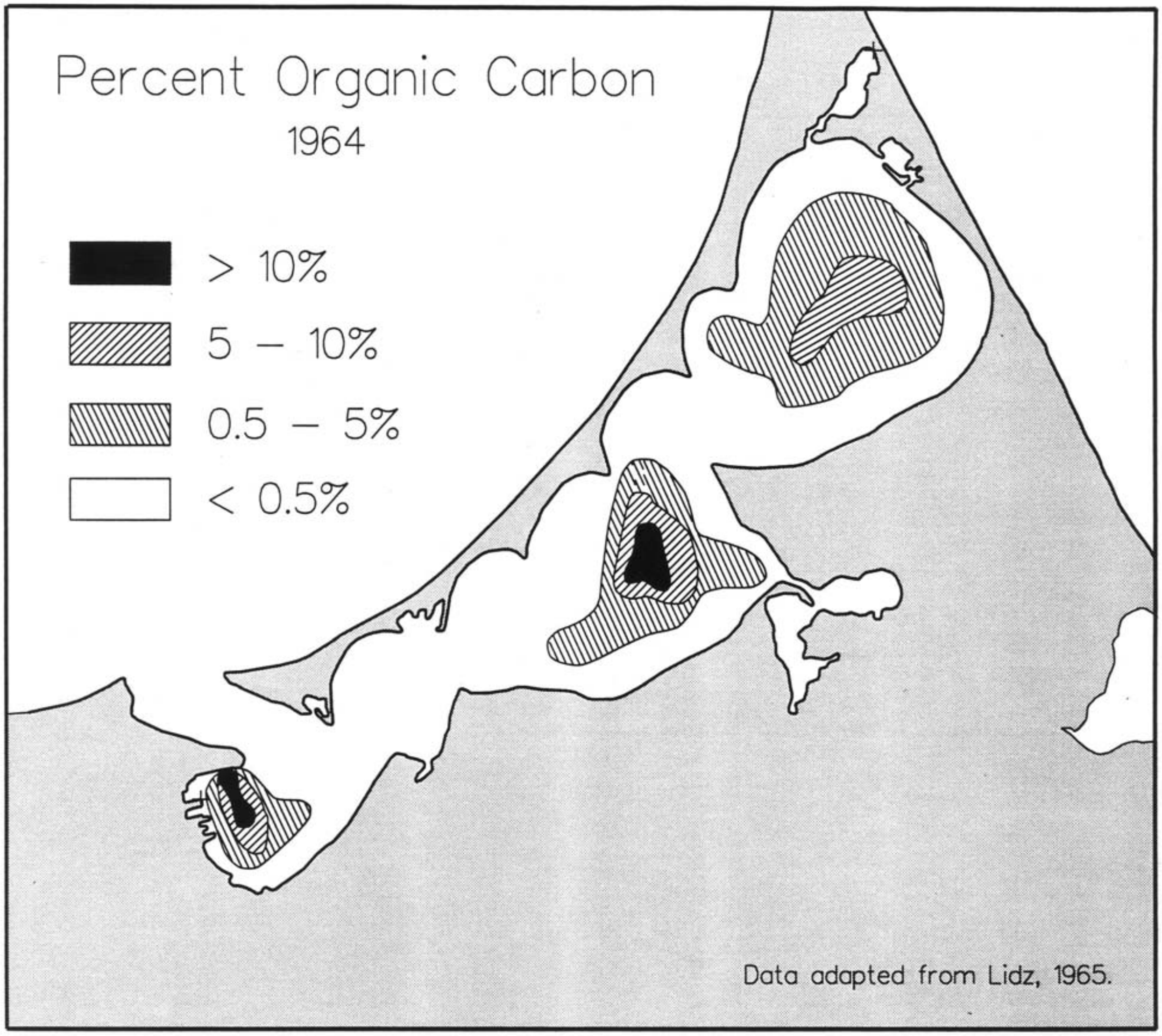


Figure I-13. Distribution of sediment organic carbon throughout Nantucket Harbor as adapted from an earlier study by Lidz, 1965. Methodological differences allow only qualitative comparisons to percentages presented in Figure I-12.

The habitat quality of the Nantucket Harbor System is significantly linked to the level of tidal flushing through its inlet to Nantucket Sound, which exhibits a moderate tide range of about 1.0 meters (3.3 feet). Since the water elevation difference between the Sound and Harbor is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle (note the tide range off Stage Harbor Chatham is ~4.5 ft, Wellfleet Harbor is ~10 ft). The inlet to Nantucket Harbor is presently stabilized with jetties to the east and west, however, the inlet to Polpis Harbor is not stabilized, but is maintained by periodic dredging.

Like the Estuary itself, the watershed areas contributing nitrogen to the harbor are distributed fully within the Town of Nantucket. The Nantucket Harbor System is one of the Town of Nantucket's significant marine resources along with Madaket Harbor. At a time when many other coastal ponds and bays in the MEP study region have been degraded, water quality in this estuary has remained high, as seen by the presence of eelgrass in the 1990's and currently.

However, the habitat quality within the terminal basin areas within the Nantucket Harbor System appear to have been gradually degrading over the past decades, as a result of nutrient overloading from its watershed, primarily resulting from residential development.

For the MEP analysis, the Nantucket Harbor System was analyzed individually as a stand-alone system. Unlike other embayment systems in the MEP study region Nantucket Harbor is an estuary with relatively limited freshwater input from streams. Direct groundwater discharge represents the majority of the freshwater flow to the estuarine system (with the exception of

Polpis Harbor which is dominated by fresh surfacewater flows) and tidal exchange of marine waters from Nantucket Sound (tide range of approximately 1.0 m) at the mouth. For the MEP analysis, the Nantucket Harbor estuarine system was partitioned into several regions: 1) the main Town sub-basin commonly considered as the most active portion of the Harbor, 2) Quaise sub-basin bounded by second point on Coatue and Pocomo Head, 3) Polpis Harbor sub-basin which receives freshwater stream discharges from Mill Brook and approximately (~) 7 other small and short creeks that drain bordering freshwater wetland 4) Head of the Harbor sub-basin (see Figure I-6). Nantucket Harbor and its associated sub-basins is a true estuary, acting as the mixing zone of terrestrial freshwater inflow and saline tidal waters from nearshore Nantucket Sound. Note that while the inflowing tidal waters originate in Nantucket Sound they are slightly influenced by processes within the nearshore basin formed by Great Point and Coatue Spit. Salinity in the Harbor and Polpis ranges from 30.4-30.8 ppt and approaches the nearshore Nantucket Sound salinity of 32 ppt. at the tidal inlet. The small amount of salinity dilution over offshore waters stems from the relatively small freshwater inflow from the watershed, the large volume of the Harbor and the relatively high rate of tidal flushing. Given the present hydrodynamic characteristics of the Nantucket Harbor embayment system, it appears that estuarine habitat quality is mostly dependent on the level of nutrient loading to embayment waters as opposed to tidal characteristics. In Nantucket Harbor, minimal enhancements to tidal flushing may be achieved via inlet or channel modification to the Harbor or the Polpis sub-estuary thereby resulting in some mediation of the nutrient inputs. The details of such are a part of the MEP analysis described later in this report.

Nitrogen loading to the Nantucket Harbor embayment system was determined relative to the regions of the estuary as depicted in Figure I-6. Based upon land-use and the watershed being entirely within a single town (Town of Nantucket), it appears that nitrogen management for harbor restoration may likely be more rapidly developed and implemented than otherwise. As management alternatives are being developed and evaluated, it is important to note the ecological differences of the major basins comprising the Estuary. The Polpis Harbor sub-estuary currently functions primarily as a small enclosed bilobate embayment. Polpis Harbor, given its enclosed nature and surface and groundwater inputs is sensitive to habitat declines related to nitrogen loading. Similarly, the Head of the Harbor acts as a deep basin with lower flushing than other larger basins due to its volume and position farthest from the inlet. It is also structured to be relatively more sensitive to nitrogen inputs than the lower large basins of Quaise and the Town. Finally, the deep, generally well flushed Quaise basin and outer Town basin containing the Steamboat wharf and working marinas function as well flushed portions of the estuary, exchanging tidal waters with Nantucket Sound. The physical characteristics interact with tidal flushing and nitrogen loading to define the nutrient characteristics of the Harbor and the associated gradients in habitat quality. Overall, the nitrogen levels in Nantucket Harbor are low to moderate compared to estuaries on Cape Cod. However, there is a slight gradient in nitrogen level and ecological health moving from the Head of the Harbor to the inlet connecting the Town basin to Nantucket Sound, with highest nitrogen and lowest environmental health in the terminal areas of the system and lowest nitrogen and greatest ecological health near the inlet to Nantucket Sound. The Polpis Harbor and Head of the Harbor basins are presently showing only moderate water quality. In contrast, the Town and Quaise basins currently support high nutrient related water quality. Eelgrass is currently present throughout large portions of the Nantucket Harbor system but appears to be thinning in terminal basin areas of higher water column nutrient concentrations (e.g. Head of the Harbor and Polpis Harbor).

I.3 NITROGEN 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 Nantucket Harbor embayment system, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer mineral (Weiskel and Howes 1992). Since even Cape Cod, Nantucket and Martha's Vineyard "rivers" are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems on Cape Cod (DeSimone and Howes 1998, Weiskel and Howes 1992, Smith *et al.* 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). Tidal reaches within the Nantucket Harbor system follow this general pattern, where the primary nutrient of eutrophication in these systems 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. As nearshore coastal salt ponds and embayments are the primary recipients of nutrients carried via surface and groundwater transport from terrestrial sources, it is clear that activities within the watershed, often miles from the water body itself, can have chronic and long lasting impacts on these fragile coastal environments.

Protection and restoration of coastal embayments from nitrogen overloading has resulted in a focus on determining the assimilative capacity of these aquatic systems for nitrogen. While this effort is ongoing (e.g. USEPA TMDL studies), southeastern Massachusetts has been the site of intensive efforts in this area (Eichner et al., 1998, Costa et al., 1992 and in press, Ramsey et al., 1995, Howes and Taylor, 1990, and the Falmouth Coastal Overlay Bylaw). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the "allowable N concentration increase" or "threshold nitrogen concentration" used in previous studies had a significant uncertainty due to the need for direct linkage of watershed and embayment models and site-specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout the Nantucket Harbor system monitored by the Town of Nantucket Water Quality Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) to "tune" general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Fortunately, within the Nantucket Harbor Estuarine system, large portions of the system appear to be below the nutrient threshold and therefore are supportive of healthy aquatic habitat. Nevertheless, the Head of the Harbor and Polpis Harbor sub-basins to Nantucket Harbor appear to be just beyond their respective abilities to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated in these areas of the system and eelgrass beds remain but are gradually declining or in the case of Polpis Harbor East Basin, have been lost. The result is that nitrogen management of this system is aimed at limited restoration and limitation of new nitrogen sources rather than maintenance of existing conditions.

In general, nutrient over-fertilization is termed "eutrophication" and when the nutrient loading is primarily from human activities, it is considered "cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to the system and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within a given embayment system could potentially occur without human influence and must be considered in the nutrient threshold analysis. While this finding would not change the need for restoration, it would change the approach and potential targets for management. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a "pristine" system.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important "boundary conditions" for water quality modeling of the Nantucket Harbor System; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within the 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 Nantucket Harbor System and each of its basins: Town of Nantucket Basin, Quaise, Head of the Harbor and Polpis Harbor. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the 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 watershed delineations performed previously by the USGS, the Town of Nantucket, Horsely & Witten Inc. and the WHOI Nantucket Harbor Study. The watershed reflects the delineation in the Town of Nantucket Watershed Bylaw.

Virtually all nitrogen entering the Nantucket Harbor embayment system is transported by freshwater, predominantly groundwater, either through direct discharge or after discharging to a stream flowing to estuarine waters or through atmospheric deposition directly to the estuary surface. Concentrations of total nitrogen and salinity of Nantucket Sound source waters and throughout the Nantucket Harbor system was taken from the Town of Nantucket Water Quality Monitoring Program (associated with the Coastal Systems Program at SMAST) and from previous sampling of Nantucket Sound nearshore waters and the Harbor by MEP staff. Measurements of nitrogen and salinity distributions throughout estuarine waters of the system were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project Linked Watershed-Embayment Management Modeling Approach to the Nantucket Harbor Estuarine System (Town, Quaise, Head of the Harbor and Polpis) for the Town of Nantucket. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission, Town of Nantucket Assessors, Nantucket Planning & Economic Development Commission and Nantucket Land Council data. Offshore water column nitrogen values were derived from an analysis of monitoring stations in Nantucket Sound (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 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 each embayment was performed that included a review of existing water quality information, temporal changes in eelgrass distribution, dissolved oxygen records and the results of a benthic infaunal animal analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment 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 in a given estuarine basin and to determine the sensitivity of the habitats within the Harbor to additional nitrogen loading (e.g. buildout). The nitrogen reduction scenario used by the MEP represents only one of many solutions and is produced to assist the Town in developing a variety of alternative nitrogen management options for the Nantucket Harbor System. Finally, analyses of the Nantucket Harbor System was relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of dredging options to improve nitrogen related water quality in Polpis Harbor. The results of the nitrogen modeling for each scenario have been presented (Section VIII).

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

In most marine and estuarine systems, such as the Nantucket Harbor System, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. This approach has been formalized through the development of tools for predicting nitrogen loads from watersheds and the concentrations of water column nitrogen that may result. Additional development of the approach generated specific guidelines as to what is to be considered acceptable water column nitrogen concentrations to achieve desired water quality goals (e.g., see Cape Cod Commission 1991, 1998; Howes et al. 2002).

Most of these tools for predicting nitrogen 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 the specific conditions of each of the coastal embayments of southeastern Massachusetts, including the Nantucket Harbor System. As the MEP approach requires substantial amounts of site-specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of “data mining” and to gather additional information on an estuary’s habitat quality or unique features.

Concern over the health of the Nantucket Island embayments has resulted in a number of studies relating to the nutrient related health of the Nantucket Harbor System over the past 2 decades. These investigations include both habitat assessments and studies relating to nitrogen loading, hydrodynamics and habitat health. While the majority of the previous studies did not provide a holistic view of the Nantucket Harbor System or its sub-basins (e.g. Polpis Harbor), they provide useful information to the present MEP effort.

Early studies of the Harbor System tend to focus on its geology. One detailed study by Lidz (1965) provides useful information on the geomorphology of the Harbor, and on its sediments. The sediment distribution within the Harbor basins is shown to be related to the sorting of sediments by wave action and the generation of organic matter that falls into depositional areas. This study produced the first sediment map showing the distribution of high and low organic matter areas throughout the Harbor. This information is important relative to infaunal habitats and areas of high and low oxygen uptake and nitrogen regeneration.

Not surprising given the scallop fishery, there have been a number of studies to determine the distribution and temporal changes in eelgrass coverage within the Harbor basins. These efforts are summarized in Kelley (1989) and include mapping by Andrews in 1944 and Kelley in 1982 and 1989. These investigations show the trends in eelgrass distribution over the past half century. While some of the analysis is only semi-quantitative, due to the logistical constraints prior to modern GPS mapping tools, they are illustrative. Most importantly, is that the work by Kelley was specifically targeted at changes in eelgrass in specific locations and therefore is sufficiently robust for incorporation into the MEP analysis (see Chapter VII). Overall, it appears that eelgrass beds have been relatively stable over the past several decades. However, eelgrass once present in Polpis Harbor (East Basin) has been lost and the trend of gradual decline in the Head of Harbor beds appears to have been occurring in 1989.

As mentioned above, most of the studies on Nantucket Harbor did not provide a holistic view of the Harbor as a tidal embayment of Nantucket Sound, situated within its a watershed with specific nitrogen sources contributing to its waters. However, one report, the *Nantucket Harbor Study: A Quantitative Assessment of the Environmental Health of Nantucket Harbor for the Development of a Nutrient Management Plan, Final Report March 1997,* did provide a system-wide analysis. This investigation attempted to evaluate this estuary and its watershed within the larger regional system and to evaluate the potential for watershed nitrogen inputs (present and at build-out) to produce habitat declines within the receiving estuary. Similar to the MEP, the study did build on water quality monitoring data, conduct watershed delineation and land-use loading analysis; conduct surveys of infaunal animals, eelgrass beds and bottomwater oxygen levels; and evaluate hydrodynamics. Although this early effort did include some preliminary hydrodynamic analysis, the water quality modeling tools were not yet sufficient to conduct quantitative predictions of changes in Harbor waters associated with altering the watershed nitrogen loading rate. The present MEP analysis builds on this earlier effort and completes the quantitative water quality modeling and nitrogen management threshold determination using new approaches not available to the 1997 Harbor Study.

The Nantucket Harbor Study grew out of an effort to address concerns over the potential for water quality degradation in Nantucket Harbor in the late 1980's. The Town of Nantucket Health Department and Marine Department, the Nantucket Land Council and the Woods Hole Oceanographic Institution joined in 1987 in an effort to assess existing conditions in the harbor and to define potential problem areas. The first step was to establish a baseline water quality program. The results of the baseline water quality study indicated that different areas within the Nantucket Harbor system were showing varying levels of environmental health (Howes and Goehringer 1989). Specifically the data indicated that the Harbor was showing high nutrient related water quality, but that there was discernable nitrogen enrichment in the Head of the Harbor and Polpis Harbor basins and a general decrease in nitrogen levels moving toward the tidal inlet. The 2 inner basins also had slightly higher chlorophyll values. The data also indicated that nitrogen was the nutrient controlling the productivity and habitat quality of Nantucket Harbor, like other estuaries in the region.

The Town of Nantucket Water Quality Monitoring Program has continued from 1988 to present (2005) and the focus continues to be to gather site-specific data on the nitrogen related water quality throughout all the embayments of the Island (including Nantucket Harbor) to track water quality and habitat health. Additionally, as remediation plans for this and other various systems are implemented, the continued monitoring is planned to provide quantitative information to the Town relative to the efficacy of remediation efforts. The MEP effort builds upon the water quality monitoring program, and previous hydrodynamic and water quality analyses conducted by Applied Coastal Research and Engineering and SMAST, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Nantucket Harbor embayment system and its major sub-embayment (Polpis Harbor).

The Town of Nantucket Water Quality Monitoring Program provided the quantitative water column nitrogen data (1988-2005) required for the implementation of the MEP's Linked Watershed-Embayment Approach. The MEP effort also builds upon previous watershed delineation and land-use analyses and the embayment water quality and eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Nantucket Harbor embayment system. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the Nantucket Harbor System and to avoiding additional cost to the Town of Nantucket. The MEP analysis has been completed with matching funds provided through MassDEP to the Technical Team.

Building on the water quality program and recognizing the importance of managing the biological resources of the Harbor as part of an overall ecosystem and the need to develop management strategies before significant environmental degradation occurs, the Nantucket Harbor Study began in 1991. The project was a unique collaboration between private citizens, scientists at the Woods Hole Oceanographic Institution, land management specialists and local governments. The goal of the effort was to integrate state-of-the-art coastal and watershed ecological approaches with land-use planning and the policy concerns and education objectives of Nantucket Islanders.

The overall goal of the program was to develop management and monitoring strategies based on quantitative data to provide the most cost effective yet ecologically sound approaches toward nutrient related water quality problems. The study was designed to encompass all of the major ecological processes dominating the water quality and productivity of the harbor, including nutrient conditions, high frequency oxygen monitoring, groundwater inputs, sediment nutrient regeneration, circulation, primary production, submerged macrophyte production, and infaunal populations. By measuring all of the dominant ecological parameters in concert, a detailed understanding of the functioning of the Harbor system and its nutrient assimilative capacity was developed thus enabling predictions as to the responses to increased or decreased nutrient loading. Specific project goals were to:

- assess the existing ecological status of the Harbor under current nutrient loading
- identify areas of high, moderate and low susceptibility to nutrient based degradation
- provide the necessary information for an overall harbor management strategy aimed at preserving ecological, fisheries and aesthetic resources.

Another fundamental goal of the Nantucket Harbor Study was to directly involve students in the research aspects of the project. At the time of the report submittal approximately twenty undergraduate and graduate students had been involved with Harbor studies. Nantucket High School students were also involved from the project's inception as student volunteers and through the Nantucket Harbor Study Environmental Internship. In addition, the Nantucket Harbor Study made Nantucket Harbor a regional center for environmental education through continuing programs such as the Buzzards Bay RIM Project for teacher education and the Center for Talented Youth.

The Nantucket Harbor Study focused on specific aspects of ecological function including but not limited to hydrology, benthic infaunal communities, nutrient cycling, oxygen status and habitat quality. A freshwater hydrologic balance of the Nantucket Harbor system was developed in part to evaluate the volume of tidal exchanges within each of the Harbor basins and as a central component of the Harbor nitrogen balance. Freshwater enters the waters of Nantucket Harbor as rainfall and as groundwater and surface water inflows. Freshwater inputs can directly affect Harbor habitat quality through salinity stratification (freshwater floating on more saline water). Periodic stratification of Harbor waters increases the potential for nutrient-related water quality problems, especially oxygen depletion, by preventing the mixing of oxygen rich surface waters with bottom waters where oxygen consumption is high. Regions of potential stratification were determined from the location and volume of freshwater input and actual stratification measurements from detailed water column profiling throughout the year. Direct measures indicated that while salinity stratification did occur in a portion of the Harbor sub-basins, stratification was infrequent, generally occurring during the warmer months when potential impact was greatest. Under levels of nitrogen inputs at the time of the study, water column stratification was not sufficient to produce frequent low oxygen events. Measurements of the distribution and volume of freshwater within the Harbor sub-basins relative to the rates of freshwater inflows were also used as a method for determining water exchange between the Harbor and Nantucket Sound. This freshwater approach to evaluation of Harbor flushing rate provides an independent validation of numerically modeled circulation.

Each pathway of freshwater entry also transports nitrogen to the Harbor from both natural and anthropogenic sources. Groundwater and surface water flows are the mechanisms by which nitrogen from the upland watershed of the Harbor reach Harbor waters. Both were quantified and each is dominated by different upland nitrogen sources. Groundwater nitrogen loading was primarily the result of on-site wastewater disposal (septic systems), infiltration of lawn fertilizers and rapid infiltration associated with runoff from impermeable surfaces. Surface water nitrogen loads comprised of discharging groundwater (with its N load), surface runoff containing fertilizers and runoff from impermeable surfaces (roads and roofs) tended to contribute less nitrogen, overall than other inputs. Transport from the watershed is one of the major sources of nitrogen to the Harbor and represent the primary inputs that can be regulated. While most of the inflow volume and nitrogen is via the groundwater pathway, surface water inputs were locally important.

In addition to characterization of the hydrology associated with Nantucket Harbor, a characterization of the benthic animal community of the Harbor was also undertaken. Infaunal communities were assessed seasonally within each Harbor basin to provide a direct assessment of current habitat quality and as a validation of nitrogen assimilative capacity. The study undertook a detailed examination of the infaunal communities and nutrient cycling within the Harbor with direct benefits to the Massachusetts Estuaries Project.

The Nantucket Harbor Study determined present (1990's) levels of nutrients, plant production and oxygen levels to assess present water and habitat quality of each of the Harbor basins. As presented in the study, ecological management of Nantucket Harbor required the quantitative assessment of nutrient loading from all sources relative to the rates of removal through tidal flushing, denitrification and sediment burial. Nutrient impacts were determined primarily by the location and total mass of nutrient inputs. The primary nutrient controlling the health of the Nantucket Harbor ecosystem was found to be nitrogen. Nitrogen was found to enter the harbor primarily from the surrounding watershed, the atmosphere and in tidal exchanges with Nantucket Sound. Nitrogen recycled within the Harbor through biological activities in the watercolumn and sediments was also measured. As such, a quantitative nitrogen balance for each of the sub-basins of the Harbor was constructed in order to determine the role of anthropogenic versus natural nitrogen sources and to identify the key pathways of nitrogen input and output from the system. The nitrogen balance was integrated with assessments of habitat quality throughout the Harbor systems to determine the ability of each Harbor system to absorb nitrogen inputs without concomitant degradation (assimilative capacity) and to provide a basis for prediction of potential changes due to increasing or decreasing nitrogen loads.

At the time of the study, Nantucket Harbor systems were found to be supporting relatively high water quality. However, nutrient levels within the Harbor were found to be higher than adjacent Nantucket Sound waters. The elevated nutrient levels within the moderately well flushed Harbor were found to be the result of both the concentration of nutrient inputs from the surrounding watershed and the seasonal storage and release of nutrients by Harbor sediments. Nutrient enrichment of the Harbor system was supported by the 2-3 fold higher rates of plant production within the watercolumn and oxygen uptake by sediments in comparison to the adjacent "pristine" habitat of Nantucket Sound. At the time of the study, oxygen levels in the deep holes in the 2 major sub-basins (Quaise and Head of the Harbor) indicated that these basins were close to their assimilative capacity for nitrogen, with periodic moderate oxygen declines.

Based on the work undertaken during this initial in-depth investigation into the function of Nantucket Harbor, specific recommendations were developed as follows:

1) From a purely nutrient related water quality view, land acquisition to protect harbor water quality should focus on larger tracts of less expensive, non-harbor front properties, especially in the Wauwinet Watershed. Economically (purchase costs + tax base) it is generally most cost-effective to purchase inland tracts.

2) Wastewater:
    a) Residential wastewater should be discharged to the sewerage system (as possible), which exports nutrients from the harbor watershed.
    b) Denitrifying septic systems may be encouraged but, except possibly in the Polpis Harbor sub-watershed, the positive impact would likely be small.

3) For both coliform and nutrient issues, direct discharge of stormwater to the harbor should cease.

4) Harbor pump-out facilities should continue to be supported and the non-discharge zone enforced.

5) Reduction of lawn fertilizer usage presents a cost-effective mechanism to significantly reduce terrestrial nitrogen inputs to the Harbor when compared to wastewater treatment options (#2).

6) Need to determine the role of eelgrass deposition in the oxygen depletion of Quaise and Wauwinet Basins. Approaches to scallop fishing which minimize "mowing" of eelgrass beds should be investigated. An evaluation of the feasibility of limiting the period for dredging of scallops within the Harbor to November - January should be

performed. Only a small fraction (ca. 12%) of the total annual catch occurs in February and March.

7) Runoff from impermeable surfaces (rooftops and driveways) should be discharged to vegetated surfaces where possible (not to subsurface rapid infiltration where groundwater will be contaminated).

8) Circulation within the harbor subsystem, particularly Polpis Harbor and Wauwinet, must be maintained.

The Nantucket Harbor Study results and data were reviewed by the MEP Technical Team and found to be of sufficient quality for incorporation (as appropriate) in the MEP analysis of the Nantucket Harbor System. This resulted in the ability of the MEP to conduct its Linked Watershed-Embayment Management Modeling Approach at no additional cost to the taxpayers of the Town of Nantucket.

In parallel with these efforts was the development of a Nantucket and Madaket Harbor Action Plan (1993), which was coordinated by the Nantucket Harbor Planning Advisory Committee under the direction of the Board of Selectman and Massachusetts Coastal Zone Management. Development of the 1993 Harbor Management Plan was the culmination of a five year community effort with the specific mission of 1) examining the current condition of Nantucket's Harbors (including Madaket Harbor) and associated water fronts and 2) to develop a comprehensive plan to include recommendations on policies and actions. Implementation of recommended policies and actions by the Town of Nantucket and County Boards were envisioned to preserve the multiple yet inter-related uses of the harbors of the Island into the future. The goals of this effort continue to present.

The MEP Technical Team identified additional recent studies related to Nantucket Harbor's habitat quality. These efforts are also summarized in the Nantucket Harbor Watershed Work Group Report (2003). BUMP conducted a watershed nitrogen loading analysis to Nantucket Harbor (2000) as part of a larger contract to Applied Science Associates (ASA) for nutrient modeling. The study did not look at the Harbor itself. The BUMP study used the Waquoit Bay watershed approach which attempts to track nitrogen from all sources through all of the biological conversions and finally to the bay. Atmospheric deposition and nitrogen recycling within the Harbor were not part of this effort or as stated by the Work Group, "Because the BUMP Study is a watershed model, and deals only with applications of N from land within the watershed, atmospheric contribution in that report are strictly limited to those contributions on land." As opposed to their proper interpretation of the Harbor Study loading data, "deposition of N on the surface waters of the Harbor is... the greatest contributor of N to the Harbor of any source." The Harbor Study and the BUMP study tended to agree as to the most important sources of nitrogen within the watershed, but the BUMP study suggested very high rates of nitrogen removal during transport to the Harbor waters, which were not validated. This model was evaluated with other models in a MassDEP and USEPA effort and found to generally underestimate watershed nitrogen loads compared to the other management models employed in southeastern Massachusetts (Howes et al. 2001). The ASA Harbor Nutrient Model was also assessed by the Work Group, "to be of limited worth, due to technical difficulties in running the model. The analyses of various structural solutions led the Work Group to conclude that such solutions may not provide the water benefits that it had hoped for. The "solution" of developing a permanent breach in the barrier beach at the Head of the Harbor raises more questions than it answers at the present time and requires further study if it is to be seriously considered." Information from these efforts has been incorporated into the present effort, as appropriate.

Consistent with its holistic evaluation of the Harbor within its watershed, the Nantucket Harbor Study has been used for planning related to Nantucket Harbor, since 1997 and provided a scientific basis for the Nantucket Harbor Watershed, created by the Town to focus planning for Harbor protection in 1999. The purpose of the "Nantucket Harbor Watershed" is stated in Chapter 99 of the Nantucket Code. "It is in the public interest to delineate the boundaries of he Nantucket Harbor Watershed, thus providing a frame of reference for diverse, multi-jurisdictional strategies and activities....In the future, these activities might include structural improvements (i.e. dredging or other activities to enhance water circulation, extension of sanitary sewers to mitigate septic nutrient loading and the development of planning contingencies....It is also important that educational strategies, devised to inform the public of ways to preserve Harbor water quality , have a defined watershed as a frame of reference". Clearly, the Town of Nantucket was forward thinking toward the protection of its Harbor resources and cognizant that without planning those resources could be lost. It is the MEP Technical Team's hope that the present MEP Technical Report will contribute to the multi-decadal effort of protecting Nantucket Harbor's resources.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

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

During the development of the Nantucket Water Resources Management Plan, an island-wide groundwater mapping project, using many of the USGS wells, was completed to characterize the water table configuration (Horsley, Witten, Hegeman, 1990). Estuary watershed delineations completed in areas with relatively transmissive sand and gravel deposits, like most of Cape Cod and the Islands, have shown that watershed boundaries are usually better defined by elevation of the groundwater and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). This approach was used by Horsley, Witten and Hegeman, Inc. (HWH) to complete a watershed delineation for Nantucket Harbor (Figure III-1); this watershed delineation has been largely confirmed by subsequent water table characterizations (*e.g.*, Lurbano, 2001, Gardner and Vogel, 2005). These watersheds have been adopted by the town as the Harbor Watershed Protection District (http://www.nantucket-ma.gov).

III.2 NANTUCKET HARBOR CONTRIBUTORY AREAS

MEP staff compared the HWH Harbor watershed to a 2004 aerial base map. This comparison found some slight discrepancies likely based on a better characterization of the shoreline; changes were made based on best professional judgment and watershed/water table characterization experience in similar geologic settings. Figure III-2 provides an overlay comparison of the HWH Harbor watershed and the revised MEP watershed. There is no overall change in the area of the two watershed delineations but there area some slight changes in the area of the Polpis, Quaise, and Head of the Harbor subwatersheds. Overall, there are four (4) subwatersheds within the Nantucket Harbor system watershed.

Table III-1 provides the daily discharge volumes for various 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 tidal hydrodynamic models. The recharge rate was developed based on calibration of the Cape Cod groundwater models prepared by the USGS and used to delineate estuary watersheds for the MEP (Walter and Whealan, 2005). This recharge rate is also consistent with the upper portion of a range of calculated recharge on Nantucket based on tritium measurements (Knott and Olimpio, 1986). The overall estimated groundwater flow into Nantucket Harbor from the MEP delineated watershed is 61,147 m3/d.

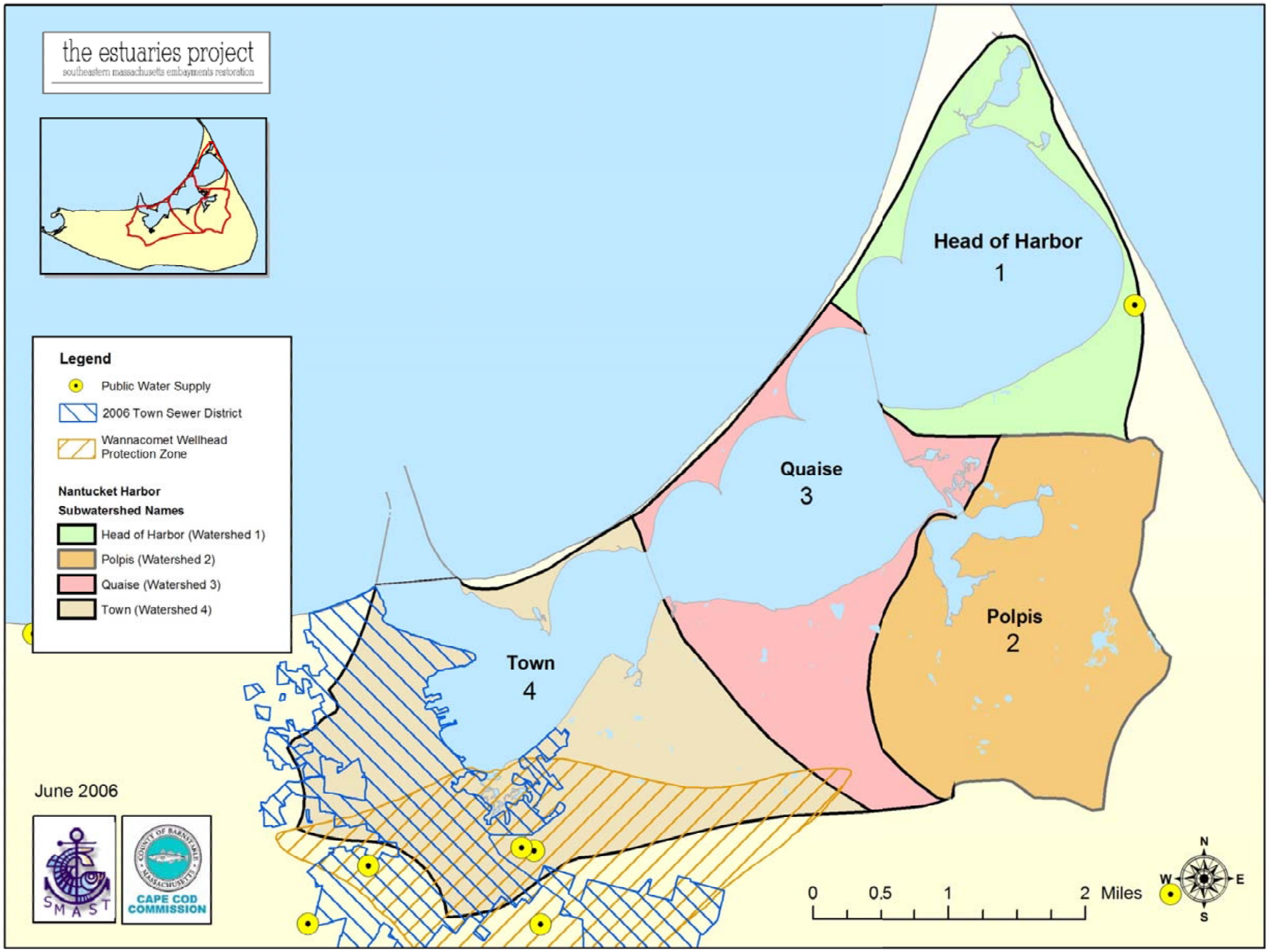


Figure III-1. Watershed and sub-watershed delineations for the Nantucket Harbor estuary system. Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI).

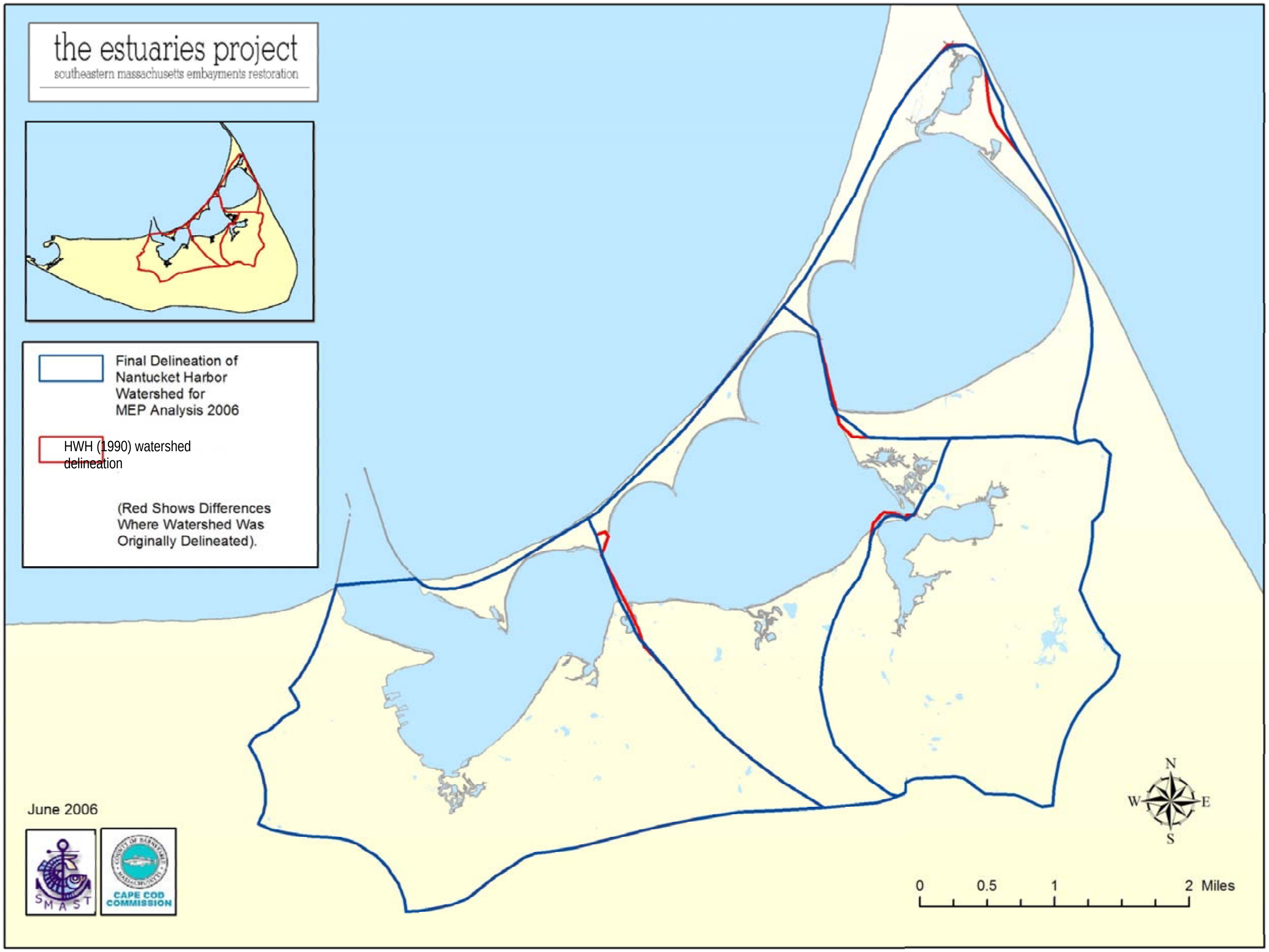


Figure III-2. Comparison of 1990 HWH and current Nantucket Harbor watershed and subwatershed delineations.

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

Watershed	Watershed #	Discharge	
		m^3/day	ft^3/day
Head of the Harbor	1	7,429	262,358
Polpis	2	20,386	719,931
Quaise	3	10,752	379,712
Town	4	22,580	797,395
TOTAL		61,147	2,159,396

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

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

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

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

The MEP Technical Team includes technical staff from the Cape Cod Commission (CCC). In coordination with other MEP Technical Team members, CCC staff developed nitrogen-loading rates (Section IV.1) to the Nantucket Harbor embayment system from its associated watershed (Section III). The Nantucket Harbor watershed was sub-divided to define contributing areas to each of the major inland freshwater systems and to each major sub-embayment to Nantucket Harbor. A total of four (4) sub-watersheds were delineated for the Nantucket Harbor estuarine system. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to each portion of the embayment (see Section III).

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other detailed studies is applied to other portions. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon subwatershed-specific land uses and pre-determined nitrogen loading rates. For the Nantucket Harbor embayment system, the model used Town of Nantucket land-use data transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as average town water use and sewered properties). 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 has not yet been included. Streamflow and associated surface water attenuation is included in the MEP's nitrogen attenuation and freshwater flow investigation, presented in Section IV.2.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. However, the watershed to Nantucket Harbor contains only smaller aquatic features that do not have separate watersheds delineated and, thus they are not explicitly included 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 the four sub-watersheds that directly discharge groundwater to the estuary. Internal nitrogen recycling was also determined throughout the tidal reaches of the Nantucket Harbor Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Estuaries Project staff obtained digital parcel and tax assessors data from the Town of Nantucket Geographic Information Systems Department. Digital parcels and land use/assessors data are from 2003. These land use databases contain traditional information regarding land use classifications (MADOR, 2002) plus additional information developed by the town. The parcel data and assessors' databases were combined for the MEP analysis by using the Cape Cod Commission Geographic Information System (GIS).

Figure IV-1 shows the land uses within the Nantucket Harbor Estuary watershed area. Land uses in the study area are grouped into eight land use categories: 1) residential, 2) commercial, 3) industrial, 4) undeveloped (including residential open space), 5) agricultural, 6) public service/government, including road rights-of-way, 7) uncategorized (e.g. parcels that do not have information in the town assessor's database) and 8) freshwater (e.g., ponds). These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2002). "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (e.g., wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges.

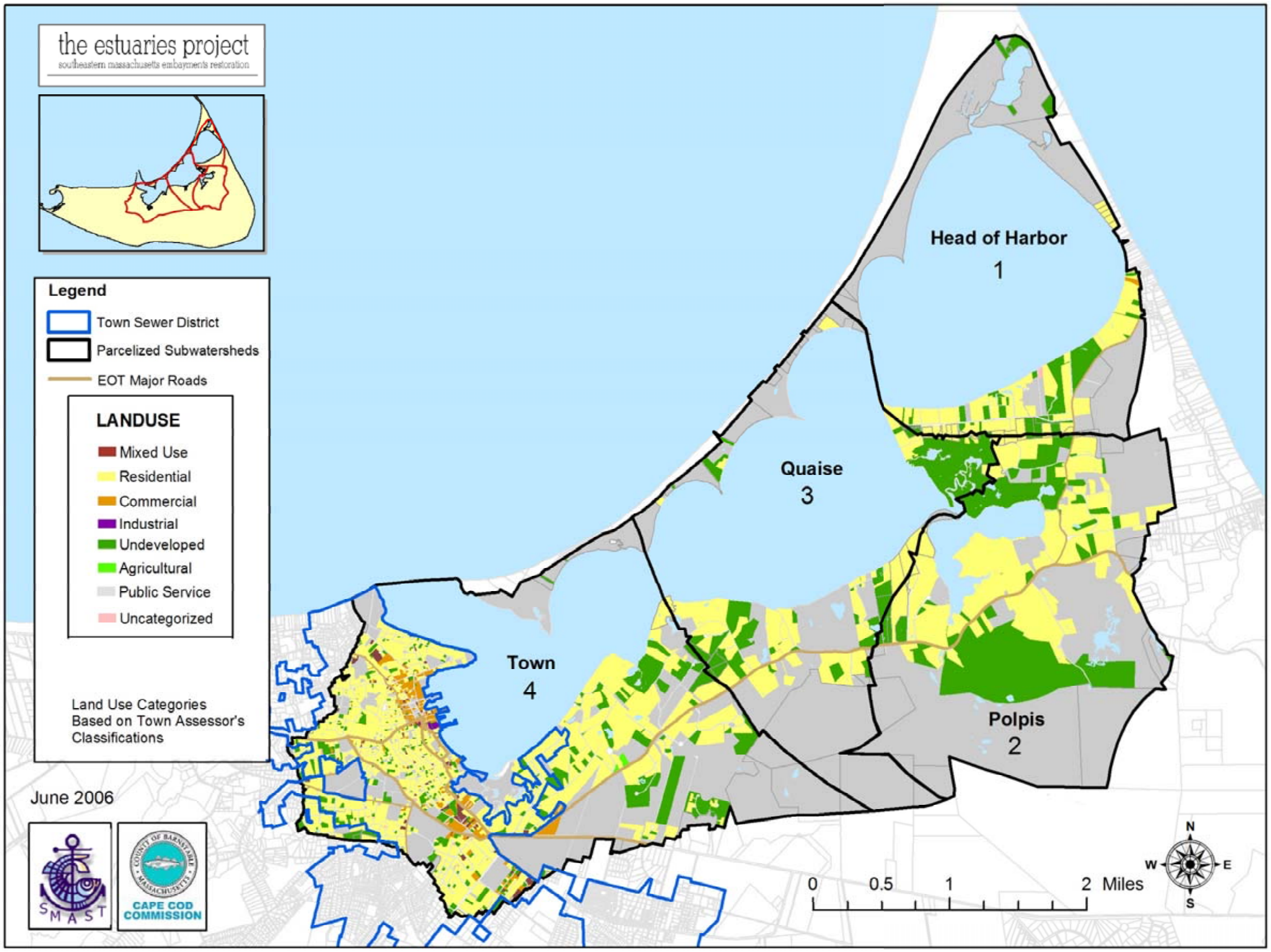


Figure IV-1. Land-use in the Nantucket Harbor watershed. The watershed is completely contained within the Town of Nantucket. Land use classifications are based on assessors' records provided by the town.

In the overall Nantucket Harbor System watershed, the predominant land use based on area is public service (government owned lands, roads, and rights-of-way), which accounts for 55% of the watershed area; residential is the second highest percentage of the system watershed (29%) and presented in Figure IV-2. However, 69% of the parcels in the system watershed are classified as residential. Single-family residences (MADOR land use code 101) are 67% of the residential parcels, but 101s and 109s (multifamily residences) are roughly the same percentage of the residential land area (47% and 48%, respectively). Public service land uses are the dominant land use category in each of the individual subwatersheds, varying between 48% and 64% of the land area. Residential land uses vary between 21 and 38% of the subwatershed areas. Undeveloped parcels are the second highest parcel count (12%) after residential in the system watershed with 10 to 27% of the parcel counts in the subwatersheds. Overall, undeveloped land uses account for 14% of the entire Nantucket Harbor watershed area, while commercial properties account for approximately 1% of the watershed area.

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. Cape Cod Commission staff contacted Mark Willette of the Wannacomet Water Company (WWC) for watershed specific water use data. At the time of the request, the WWC was in the process of developing parcel-by-parcel water use information, but would not have it developed in time to complete the MEP analysis. Mr. Willette graciously offered to review 2005 water use records for approximately 130 residential accounts. This review found the average residence used 1,703 cubic feet per year with a range among the accounts reviewed of 108 to 5,150 cubic feet per year. The average water use translates into 12,738 gallons per year or 35 gallons per day; this average was used as a proxy for residential wastewater generation in the Nantucket Harbor watershed. Select parcels within the watershed, mostly within the Town subwatershed, are also connected to the municipal sewer system, which discharges outside of the Harbor watershed; these parcels have zero wastewater nitrogen loads in the watershed nitrogen loading analysis. Parcels connected to the town sewer system were identified in the records obtained from the town. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the average water-use, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2).

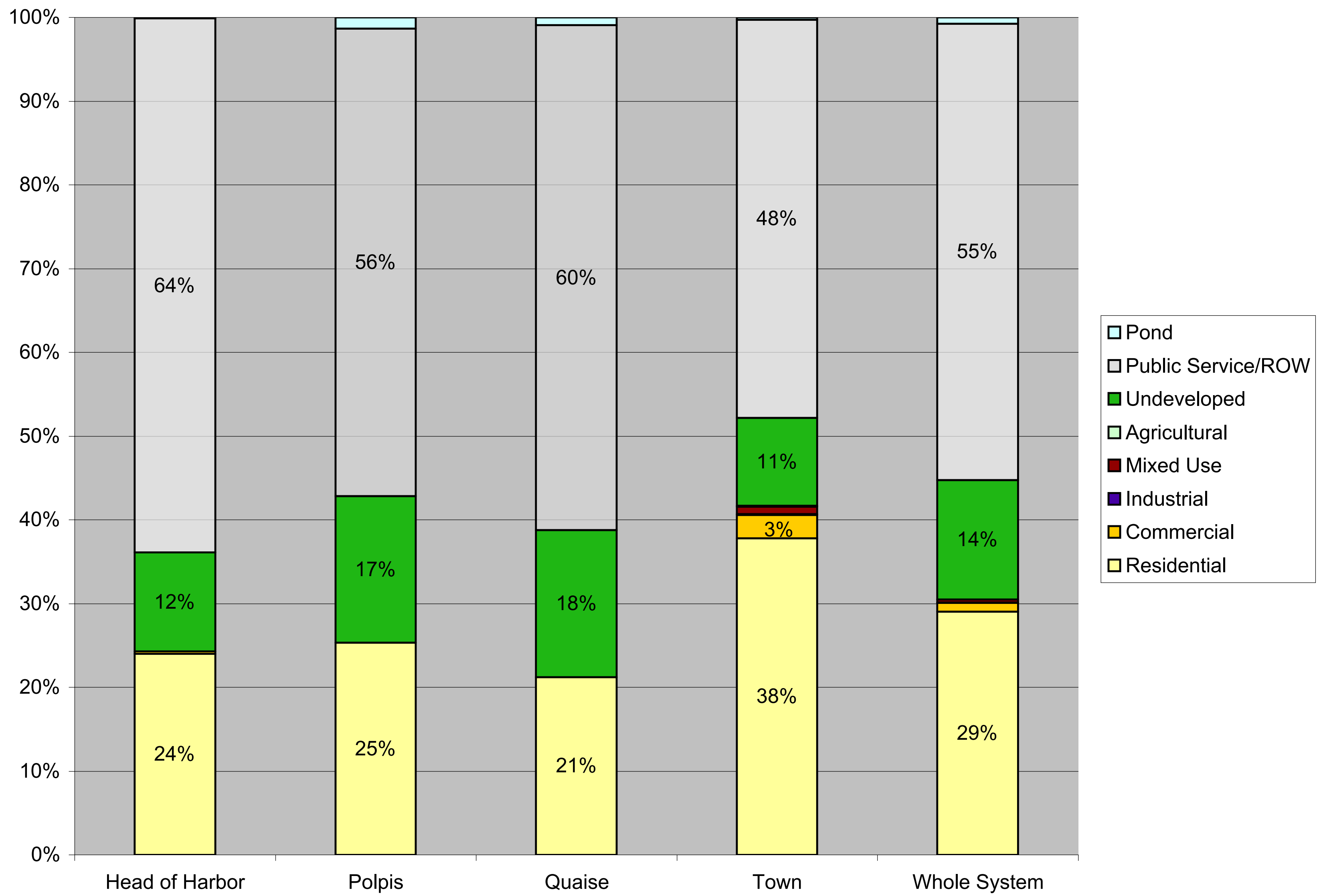


Figure IV-2. Distribution of land-uses within the subwatersheds and whole watershed to Nantucket Harbor. Only percentages greater than or equal to 3% are shown.

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. 2002). Variation in per capita nitrogen load has been found to be relatively small, with average annual per capita nitrogen loads generally between 1.9 to 2.3 kg person-yr^{-1}.

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

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

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

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

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

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

In order to provide an independent validation of the average residential water use within the Nantucket Harbor System watershed, MEP staff reviewed US Census population values for the Town of Nantucket. The state on-site wastewater regulations (310 CMR 15.000, 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 the 2000 US Census data, the average occupancy within Nantucket is 2.57 people per occupied housing unit, while year-round occupancy of available housing units is 40%. If the average occupancy is multiplied by 55 gpd, the average water use for occupied units is 142 gpd. However, because the majority of the residential units on Nantucket are not occupied, the average occupancy of all units is 1.03 people per house and if this is multiplied by the regulatory 55 gpd flow per person, the average water use drops to 57 gpd. This flow is still higher than the average determined from the water use review, but it suggests that the water use average is reasonable given the high percentage of seasonally occupied dwellings.

In most previously completed MEP studies, average population and average water use have generally agreed fairly well. Since the Nantucket Harbor analysis is dependent on a water use average rather than parcel-by-parcel water use, MEP staff also reviewed more refined US Census information and 1990 Census information. Besides reviewing data at the town and state levels, the US Census also develops information for smaller areas (i.e., tracts and block groups). Portions of two Census tracts are contained within the watershed to Nantucket Harbor; tract 9501, which generally covers the Town subwatershed, and tract 9505, which generally covers the remaining three subwatersheds. Year 2000 Census residential occupancy rates in the tracts are 2.44 and 2.26 people per house, respectively, while the average occupancy of all units is 0.78 and 0.53, respectively. The percentage of occupied housing units is 32% and 22%, respectively. The 1990 tracts are not the same areas as the 2000 tracts, but the averages tend to be similar to those from 2000.

It is clear from this analysis that the average occupancy in the Nantucket Harbor watershed is lower than the town-wide average. If the average occupancy of all units is multiplied by the regulatory 55 gpd per person, the average water use in Tract 9501 is 43 gpd, while the average in Tract 9505 is 29 gpd. The 35 gpd average flow determined from a review of WWC accounts fits within this range and this analysis suggests that this average flow is an appropriate basis for determining residential wastewater nitrogen loads within the Nantucket Harbor watershed.

Commercial and industrial properties were treated differently than residential parcels. There are a total of 308 commercial properties in the Nantucket Harbor watershed with 307 of them located in the Town subwatershed. There are five industrial properties, all of which are located in the Town subwatershed. Commercial and industrial properties were assigned a water use based on percentage of parcel building coverage and average water uses for commercial properties determined through the MEP technical review of the Three Bays and Eel Pond/Back River watersheds.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and cranberry bogs, with lawns being the predominant source within this category. In order to add this source to the nitrogen-loading model for the Nantucket Harbor system, MEP staff reviewed available information about residential lawn fertilizing practices. No golf courses or cranberry bogs were identified within the watershed. Large government turf areas were identified from aerial photographs in the Town subwatershed; these were assumed to have the same nitrogen load as residential lawn areas.

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

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

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the Cape Cod Commission's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and Massachusetts DEP's Nitrogen Loading Computer Model Guidance (1999). The recharge rate for natural areas and lawn areas is the same as utilized in the MEP-USGS groundwater modeling effort (Section III). Factors used in the MEP nitrogen loading analysis for the Nantucket Harbor 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, parcels were assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel was located within a respective watershed. Following the assigning of boundary parcels, all large parcels were examined individually and were split (as appropriate) in order to obtain less than a 2% difference between the total land area of each subwatershed and the sum of the area of the parcels within each subwatershed. The resulting "parcelized" watersheds to Nantucket Harbor are shown in Figure IV-3.

Table IV-1. Primary Nitrogen Loading Factors used in the Nantucket Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Barnstable data. *Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.

Nitrogen Concentrations:	mg/l	Recharge Rates:	in/yr
Road Run-off	1.5	Impervious Surfaces	40
Roof Run-off	0.75	Natural and Lawn Areas	27.25
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:	
Natural Area Recharge	0.072	Existing developed residential parcels and buildout residential parcels:	35 gpd
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (ft^2)*	5,000	Commercial and industrial parcels and buildout additions:	21 gpd/1,000 ft2 of building
Residential Watershed Nitrogen Rate (lbs/lawn)*	1.08		
		Commercial and industrial building coverage accounts and buildout additions:	28%

The 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 (condominiums, golf courses, 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 Nantucket Harbor 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.

Following the assignment of all parcels, subwatershed modules were generated for each of the four sub-watersheds summarizing water use, parcel area, frequency, sewer connections, private wells, and road area. The individual sub-watershed modules were then integrated to create the Nantucket Harbor Watershed Nitrogen Loading module with summaries for each of the individual subembayments. The subembayments represent the functional embayment 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 Nantucket Harbor System, the major types of nitrogen loads are: wastewater (e.g., septic systems), fertilizer, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the watershed nitrogen loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-4 a-e). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model.

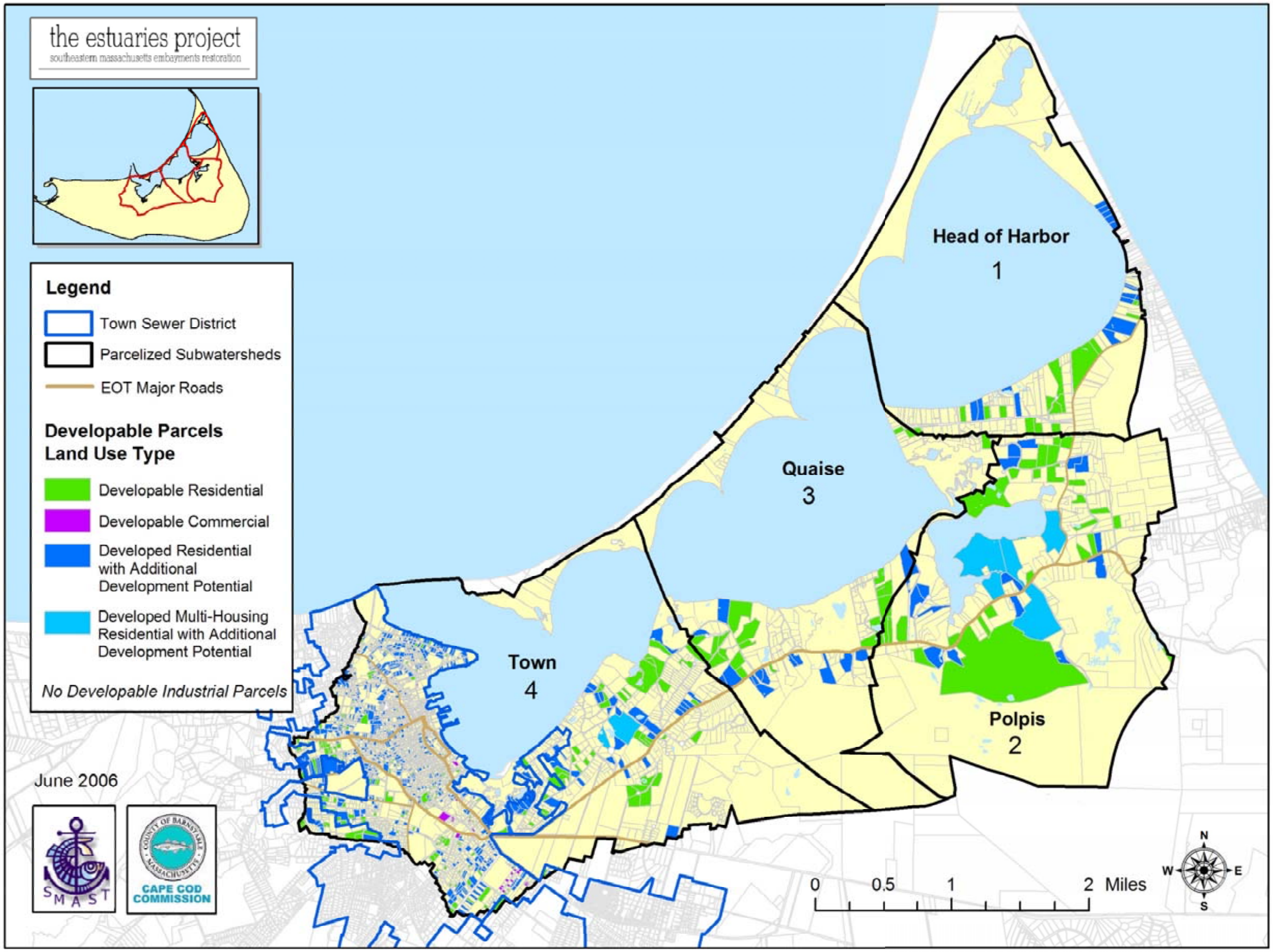


Figure IV-3. Parcels, Parcelized Watersheds, and Developable Parcels in the Nantucket Harbor watersheds.

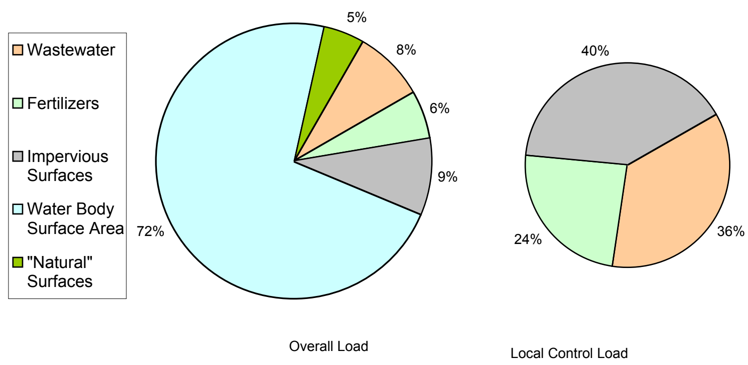
Table IV-2 (a-b). Nantucket Harbor Nitrogen Loads. (a) presents nitrogen loads based on current conditions including removal of wastewater nitrogen loads from the watershed by current connections to the municipal sewer system. (b) presents nitrogen loads based on the connection of all existing and buildout properties within the sewer district to the municipal sewer system and the removal of their wastewater nitrogen loads from the watershed. All values are kg N yr^{-1}.

ALT BO for Town subwatershed		*Nantucket Harbor N Loads by Input (kg/y):*						% of Pond Outflow	*Present N Loads*			*Buildout N Loads*		
Name	Watershed ID#	Wastewater	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Nantucket Harbor		1112	1677	2743	21591	1411	2028		28534		28534	30562		30562
Head of the Harbor		257	55	174	8123	186	189		8795		8795	8984		8984
Head of the Harbor	1	257	55	174	5	186	189		678		678	867		867
Head of the Harbor Estuary surface deposition					8117				8117		8117	8117		8117
Polpis		158	67	393	958	512	206		2087		2087	2294		2294
Polpis	2	158	67	393	158	512	206		1288		1288	1494		1494
Polpis Estuary surface deposition					799				799		799	799		799
Quaise		144	59	246	7404	269	103		8121		8121	8225		8225
Quaise	3	144	59	246	58	269	103		775		775	878		878
Quaise Estuary surface deposition					7346				7346		7346	7346		7346
Town		552	1496	1931	5107	444	1529		9530		9530	11059		11059
Town	4	552	1496	1931	38	444	1529		4461		4461	5990		5990
Town Estuary surface deposition					5069				5069		5069	5069		5069

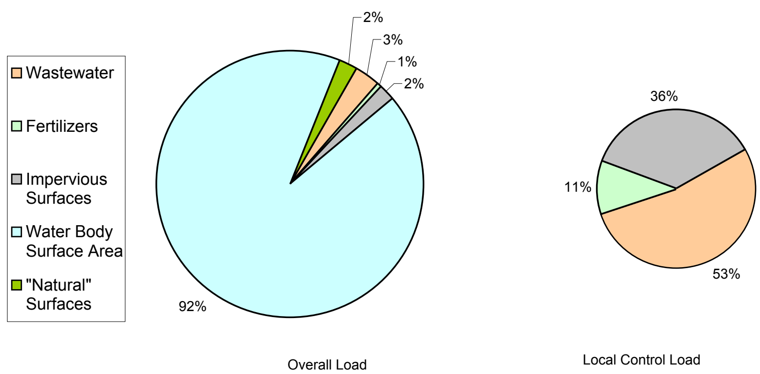
a. Present and buildout loads under current conditions with no increase in sewer connections

		Nantucket Harbor N Loads by Input (kg/y):						% of Pond Outflow	*Present N Loads*			*Buildout N Loads*		
Name	Watershed ID#	Wastewater	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Nantucket Harbor		2455	1677	2743	21591	1411	2028		29877		29877	31905		31905
Head of the Harbor		257	55	174	8123	186	189		8795		8795	8984		8984
Head of the Harbor	1	257	55	174	5	186	189		678		678	867		867
Head of the Harbor Estuary surface deposition					8117				8117		8117	8117		8117
Polpis		158	67	393	958	512	206		2087		2087	2294		2294
Polpis	2	158	67	393	158	512	206		1288		1288	1494		1494
Polpis Estuary surface deposition					799				799		799	799		799
Quaise		144	59	246	7404	269	103		8121		8121	8225		8225
Quaise	3	144	59	246	58	269	103		775		775	878		878
Quaise Estuary surface deposition					7346				7346		7346	7346		7346
Town		1896	1496	1931	5107	444	1529		10873		10873	12402		12402
Town	4	1896	1496	1931	38	444	1529		5804		5804	7333		7333
Town Estuary surface deposition					5069				5069		5069	5069		5069

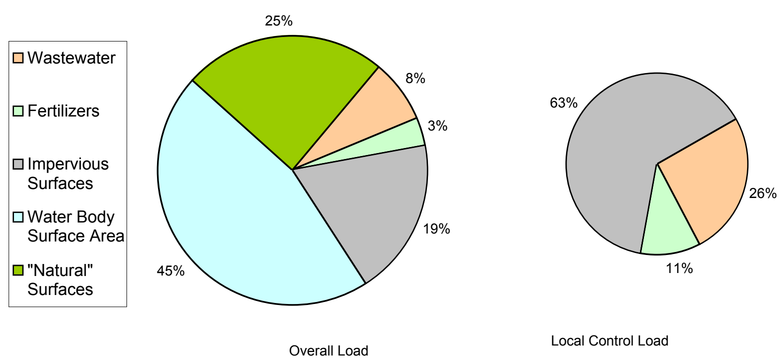
b. Buildout where all existing and future properties in sewer district are connected to the sewer system



a. Nantucket Harbor System Overall

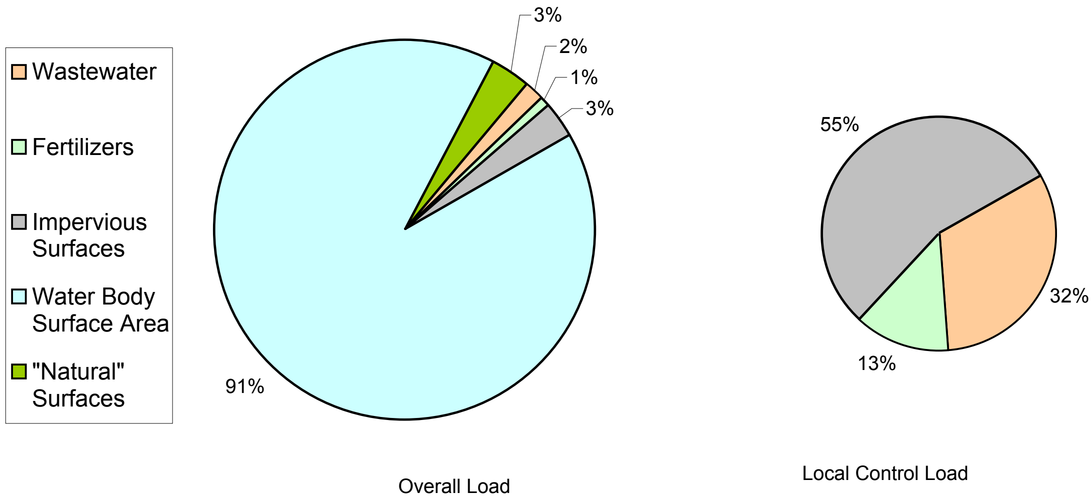


b. Head of the Harbor Subwatershed

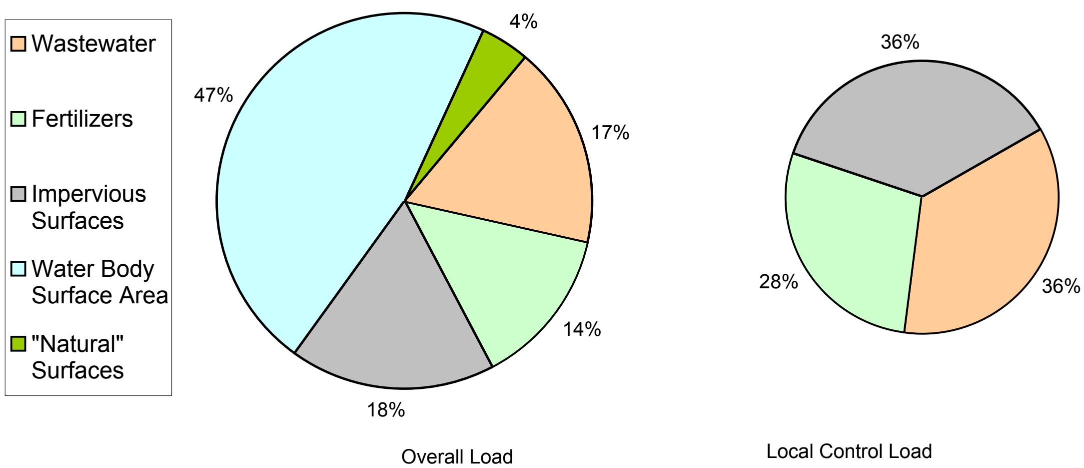


c. Polpis Subwatershed

Figure IV-4 (a-c). Land use-specific unattenuated nitrogen load (by percent) to the (a) overall Nantucket Harbor System watershed, (b) Head of the Harbor subwatershed, and (c) Polpis subwatershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.



d. Quaise Subwatershed



e. Town Subwatershed

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

Buildout

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

Table IV-2 presents two different buildout scenarios. The first scenario (Table IV-2a) is based on existing conditions; only properties currently connected to the municipal sewer system have their wastewater nitrogen load removed from the Nantucket Harbor watershed. Any additional development resulting from buildout is assumed to discharge its wastewater nitrogen within the Harbor watershed. The second scenario (Table IV-2b) assumes that all properties, both existing and any future development associated with buildout, that are located within the sewer district boundary are connected to the municipal sewer system and their wastewater nitrogen load is removed from the Harbor watershed.

Overall, a nitrogen load for each additional residence or business is included in the cumulative unattenuated buildout indicated in a separate column in Table IV-2. Buildout additions within the overall Nantucket Harbor System watershed in either scenario will increase the unattenuated loading rate by 4%.

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, sewering analysis, enhanced flushing, pond/wetland restoration for natural attenuation, etc.) 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 sub-basins of the Nantucket Harbor System (inclusive of Head of the Harbor, Polpis Harbor and the Quaise sub-basin) being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their 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 from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such as the developed region of the Nantucket Harbor System watershed). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. However, in most watersheds in southeastern Massachusetts, nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Though this is the case to a more limited extent in the watershed of Nantucket Harbor, surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the case of the Nantucket Harbor embayment system watersheds, a portion of the freshwater flow and transported nitrogen passes through a series of small surface water systems composed of small, short freshwater streams emanating from freshwater wetlands prior to entering the estuaries, producing the opportunity for a degree of nitrogen attenuation.

Though nitrogen attenuation may be small in the fresh, surface water flows discharging to Nantucket Harbor, failure to determine the attenuation of watershed derived nitrogen overestimates the nitrogen load to receiving estuarine waters. If nitrogen attenuation is significant in one portion of a watershed and insignificant in another the result is that nitrogen management would likely be more effective in achieving water quality improvements if focused on the watershed region having unattenuated nitrogen transport (other factors being equal). In addition to attenuation by freshwater ponds/wetlands (see Section IV.1.3, above), attenuation in surface water flows is also important. An example of the significance of surface water nitrogen attenuation relating to embayment nitrogen management was seen in the Agawam River, where >50% of nitrogen originating within the upper watershed was attenuated prior to discharge to the Wareham River Estuary (CDM 2000). Similarly, MEP analysis of the Quashnet River indicates that in the upland watershed, which has natural attenuation predominantly associated with riverine processes, the integrated attenuation was 39% (Howes et al. 2004). In addition, a preliminary study of Great, Green and Bournes Ponds in Falmouth, measurements indicated a 30% attenuation of nitrogen during stream transport (Howes and Ramsey 2001). An example where natural attenuation played a significant role in nitrogen management can be seen relative to West Falmouth Harbor (Falmouth, MA), where ~40% of the nitrogen discharge to the Harbor originating from the groundwater effluent plume emanating from the WWTF was attenuated by a small salt marsh prior to reaching Harbor waters. Clearly, proper development and evaluation of nitrogen management options requires determination of the nitrogen loads reaching an embayment, not just loaded to the watershed.

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, the possibility of natural attenuation of watershed nitrogen loads was considered as part of the MEP Approach. Under a previous nutrient study of Nantucket Harbor (Howes et. al., 1997) which was conducted by members of the MEP Technical Team while in residence at the Woods Hole Oceanographic Institution, as well as a site specific study of surfacewater flow and nutrient flux from the Mill Brook watershed (Millham and Howes, 1990), measurements of flow and nutrient load were conducted on 11 small streams and creeks discharging to the Head of the Harbor, Quaise and the Polpis Harbor sub-basins.

Measurement of the flow and nutrient load associated with the streams discharging to the Nantucket Harbor estuarine system provided: 1) a direct measure of the relative importance of stream discharge to the Nantucket Harbor in comparison to direct groundwater discharge as well as 2) an indication of the relative nutrient loads to the Harbor as represented by stream discharge when compared to all sources of nitrogen load to the Harbor system.

Determination of stream flow was calculated and based on the measured values obtained for stream cross sectional area and velocity. Stream discharge was represented by the summation of individual discharge calculations for each stream subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire stream cross section were not averaged and then applied to the total stream cross sectional area.

The formula that was used for calculation of stream flow (discharge) is as follows:

$$Q = \Sigma(A * V)$$

where by:

Q = Stream discharge (m^3/s)
A = Stream subsection cross sectional area (m^2)
V = Stream subsection velocity (m/s)

Thus, each stream subsection will have a calculated stream discharge value and the summation of all the sub-sectional stream discharge values will be the total calculated discharge for the stream.

In the 1997 Nantucket Harbor Study, the flow records for each of the streams indicated that the major surfacewater discharge to the Harbor was Mill Brook flowing into Polpis Harbor. As such, the MEP focused on the Mill Brook freshwater flow and associated nutrient load to determine whether or not stream related nutrient load could be a significant input term to the water quality model.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge to Quaise, Polpis and Head of the Harbor portions of the Nantucket Harbor System

The streams which enter Nantucket Harbor are relatively short and have small flows. The main exception is Mill Brook (Figure IV-5), which drains Windswept Bog and flows to the western lobe of Polpis Harbor and accounts for over 40% of the total stream inflow. Most of the other streams occur as outlets from freshwater wetlands or from small freshwater ponds in the Polpis Harbor watershed and from Squam Swamp. Discharge and nutrient levels from the predominant stream, Mill Brook, were measured continuously over the critical period for eutrophication, July-September 1990. Additionally, on four dates in 1994 flow and dissolved and particulate nutrients at the various streams discharging into Nantucket Harbor were measured. Flow in one, #6, was usually too small to measure accurately.

Stream discharges ranged more than an order of magnitude with all the small streams and showed an average of less than 2 m^3d^{-1}. Mill Brook showed a wide range of flows (approximately 700 - 4500 m^3d^{-1}). The larger discharge of Mill Brook results from its larger watershed and association with a large wetland. The second largest surface flow, Folgers Marsh Stream drains a salt marsh and freshwater wetland system with a large upland watershed. Surprisingly, stream #8 (Squam) which appears to be the principal outlet from Squam Swamp into the Head of the Harbor, has a relatively low discharge. This may indicate that the watershed which contributes to this stream may be smaller than the Horsley Witten maps suggest, or that the watershed boundaries for Squam Swamp may vary seasonally as the water table elevation changes. In such swampy, poorly drained, glacially-derived settings the delineation of watersheds without a large network of water table monitoring wells includes a degree of uncertainty.

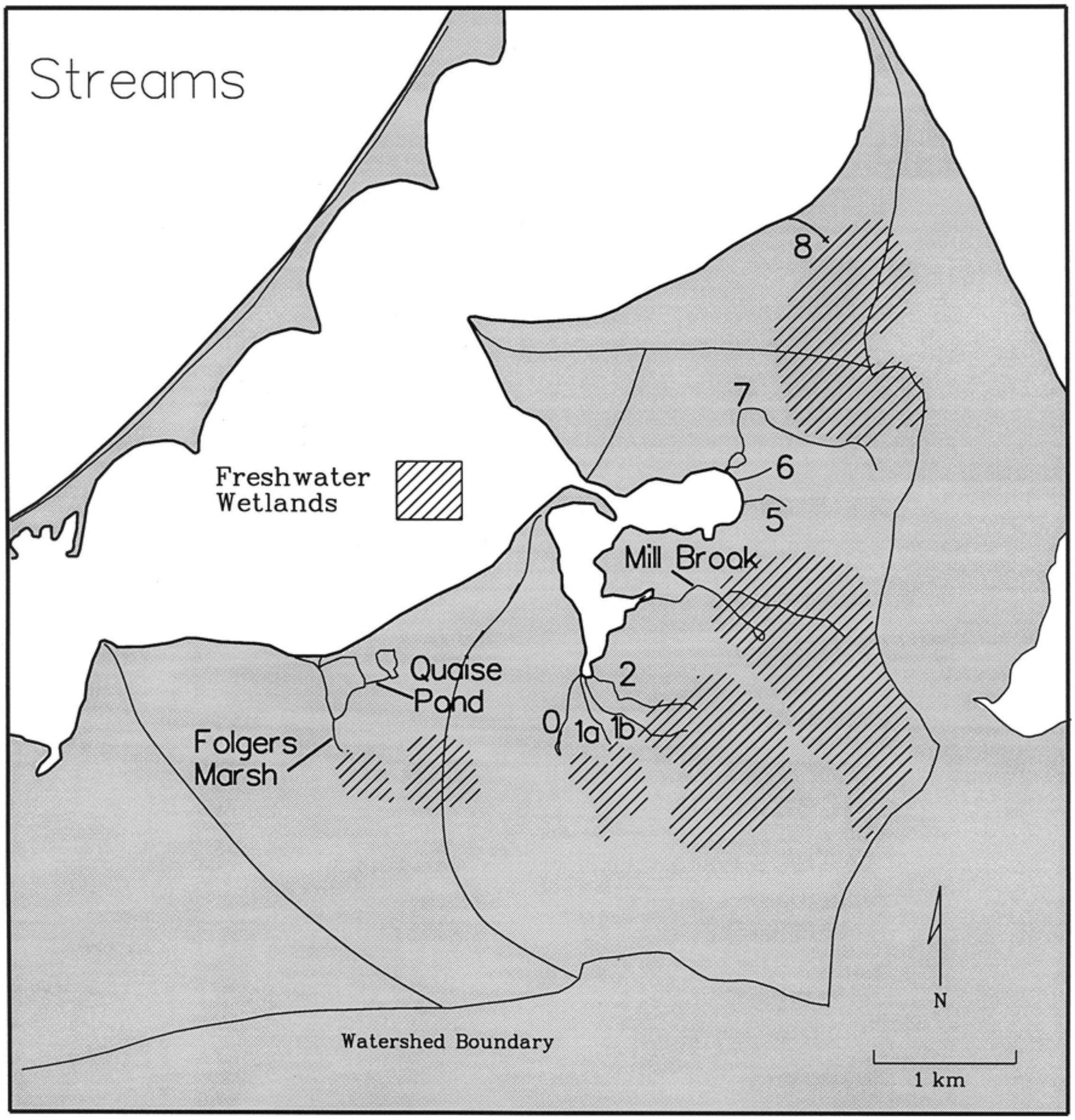


Figure IV-5. Location of major streams discharging to the Nantucket Harbor embayment system in relation to associated freshwater wetlands. Most of the streams are short and act primarily as "drains" for groundwater and conduits of stormwater runoff. Courtesy of Nantucket Harbor Study.

Stream Flow, Nutrient Concentrations and Nutrient Loads

In order to judge the degree of importance to place on the Mill Brook stream input (both in terms of flow and nutrient load) and the impact this specific stream may have on the water quality modeling of Nantucket Harbor, the MEP Technical Team compared the measured stream flow in Mill Brook (700-4500 m^3d^{-1}) to the direct groundwater discharge to Polpis Harbor (20,386 m^3d^{-1}) based on the most recent watershed delineations as presented in Section III and the MEP recharge rate of 27.25 inches per year. Annualizing these values yields a Mill Brook discharge to Polpis Harbor of 255,000 - 1,642,000 m^3yr^{-1} versus a the total freshwater discharge to Polpis Harbor of 7,440,890 m^3yr^{-1}, based upon watershed water balance The Mill Brook discharge to Polpis Harbor represents 3%-22% of the freshwater flow to the Polpis Harbor subembayment.

Nutrient concentrations in the streams were generally quite low in bioactive nitrogen. Bioactive nitrogen represents the biologically most active nitrogen forms, inorganic nitrogen which is immediately available for plant uptake and particulate organic nitrogen from which inorganic nitrogen is released after microbial degradation. Of the eleven streams, seven had mean bio-active N levels below 9 uM, the average bioactive N concentration in Polpis Harbor waters during summer (Figure IV-6). The principal exception was stream #6 which had relatively high nitrate concentrations likely indicating a localized source of nitrogen such as a septic plume or an old agricultural source. For 7 of 11 streams, the largest nitrogen constituent was particulate organic nitrogen. The low nutrient concentrations for these streams is not surprising since their source areas contain large proportions of wetlands which tend to be nutrient sinks, and because the watersheds can support only low housing densities. To put this data into better perspective, mean values for 2 streams located in Falmouth, Cape Cod in a similar geological setting but with a fully developed watershed had average DIN (NH4+NOx) concentrations of 56 and 229 uM N (Howes, et al. 1995; Howes & Goehringer 1997). These values are 8 to 32 times higher than the mean DIN for all 11 Nantucket streams of 7.05 uM.

In order to gauge the nutrient related impacts of stream transport on Nantucket Harbor, it was necessary to determine the total mass loading of nitrogen through stream discharge. It is the total mass of nitrogen not the concentration which impacts harbor systems, a stream with a high concentration but a low flow may be many times less important than one with an intermediate N concentration and continuous high discharge. The mass of nutrients which streams deliver to the harbor is the product of the N concentration and the volume of stream discharge. Mill Brook is the largest contributor of stream transported nutrients to the Harbor. Based on nutrient sampling data collected at the mouth of Mill Brook (ISCO Model 2700 automated sampling device capturing 10 nutrient samples per 24 hour period, July 11 to September 20, 1990) a total nitrogen load to Polpis Harbor of 200 kg N yr^{-1} was calculated by the MEP Technical Team (prior estimates were bioactive N). By comparison, the total watershed load of nitrogen entering Polpis Harbor based on land use analysis, the Polpis Harbor watershed area and annual recharge yields an un-attenuated load of 1288_kg N yr^{-1} (Section IV.1). Based upon the surface water flow information available for Mill Brook, we can estimate that as much as 22% of the watershed N load may discharge through this stream, or 322 kg N yr^{-1}. This might indicate as much as a 38% attenuation of nitrogen by this wetland system (measured 200 kg N yr^{-1} vs modeled 322 kg N yr^{-1}) However, there are substantial uncertainties in these stream load estimates due to the high variability of the flows and the partial year of data collection. Therefore, given that the mass of nitrogen potentially attenuated by the stream/wetland system is small relative to Polpis Harbor and negligible to Nantucket Harbor, the MEP Technical Team went forward with the more conservative approach for modeling using the unattenuated watershed nitrogen load.

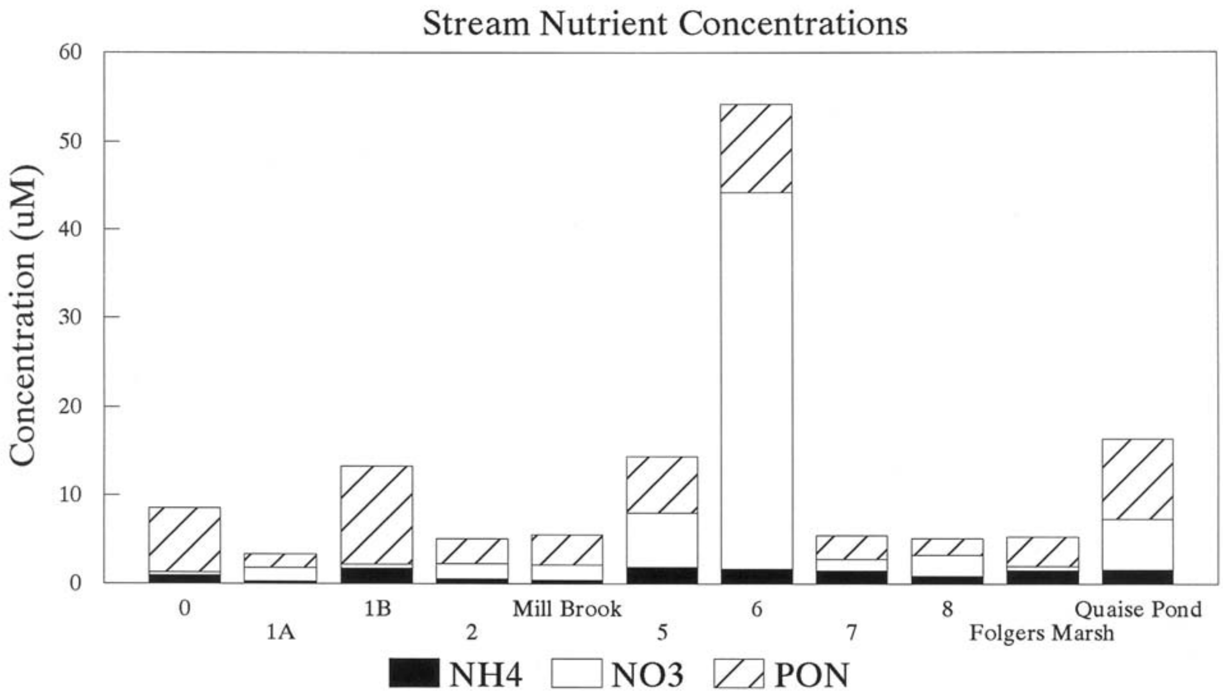


Figure IV-6. Average nutrient concentrations for 11 streams discharging to Nantucket Harbor. Nitrate (NO3) and particulate organic nitrogen (PON) constitute almost all of the bio-active nitrogen pool. The high level of N in stream 6 was primarily due to high nitrate possibly from wastewater. However, stream 6 did not have a commensurately high N load as the volumetric discharge was very small. Courtesy of Nantucket Harbor Study.

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the Benthic Nutrient Flux Surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters within each major basin area within the Nantucket Harbor embayment system. The mass exchange of nitrogen between watercolumn 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 Nantucket Harbor embayment system predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the watercolumn (once it entered), then predicting watercolumn nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the watercolumn for sufficient time to be flushed out to a downgradient larger waterbody (like Nantucket Sound). However, 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. Also, in longer 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 bays.

In general the fraction of the phytoplankton population which enters the surficial sediments of a shallow embayment: (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.

IV.3.2 Method for determining sediment-watercolumn nitrogen exchange

For the Nantucket Harbor system, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected from each of the 4 main basins throughout the Nantucket Harbor System (Figure IV-7), Head of the Harbor (4 sites), Quaise Basin (2 sites), Town Basin (3 sites) and Polpis Harbor (east basin 1 site, west basin 1 site). In the deep basins of Head of the Harbor and Quaise, sediment cores were collected in shallow (<8') and deep (>10') locations to account for differences in nitrogen exchange related to water depth. Previous study of the organic carbon distribution within these basins indicated much higher organic matter levels in the depositional areas of the deep basin compared to the shallow margins. This organic matter gradient suggested *a priori* a potentially higher rate of nitrogen release from the deep versus shallow sediments in these basins. Given the high velocities of water through the tidal inlet, the area seaward of Brant Point employed data from a station just outside of the jetties (OS9). Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

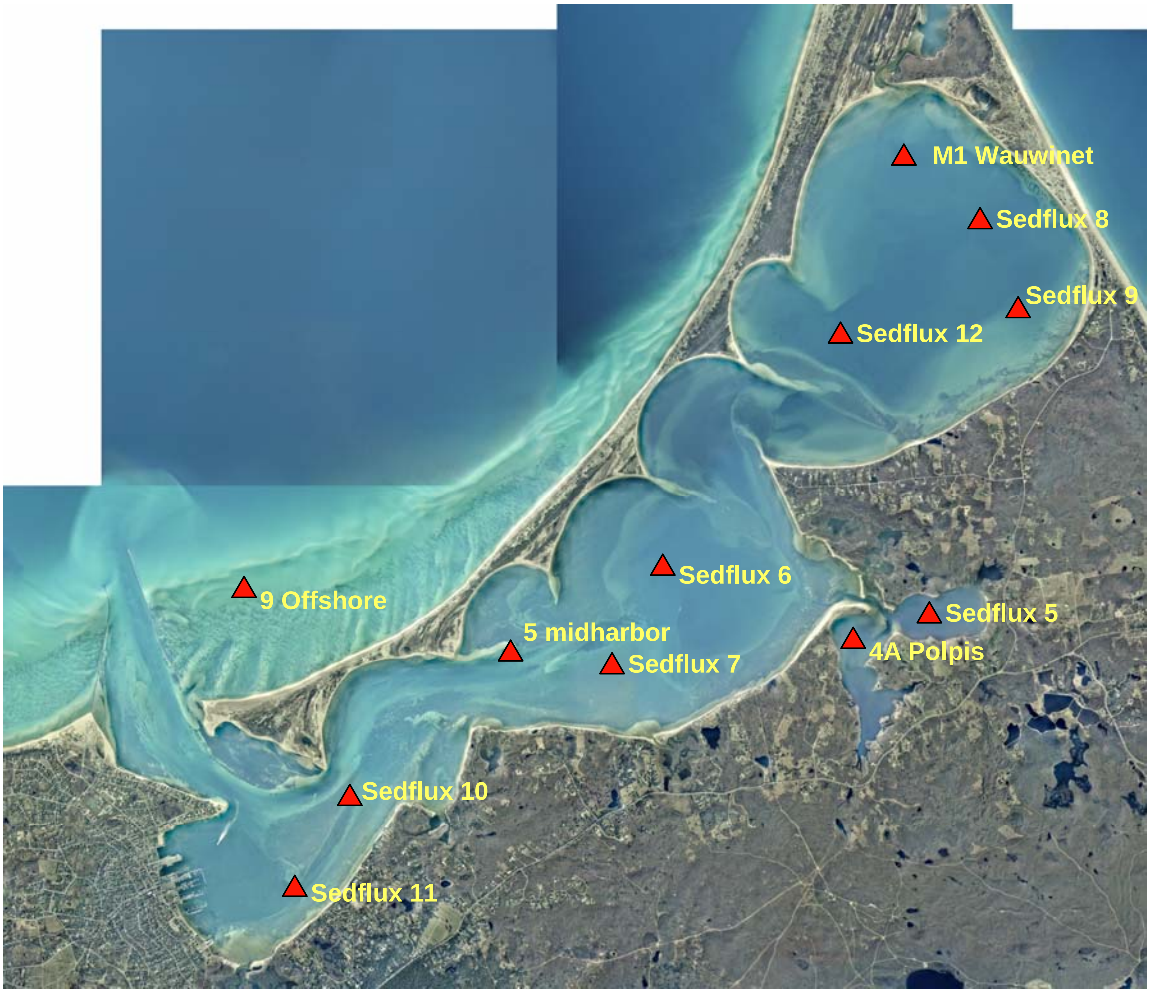


Figure IV-7. Nantucket Harbor embayment system sediment sampling sites (red symbols) for determination of nitrogen regeneration rates.

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-7) per incubation were as follows:

Head of the Harbor Basin Benthic Nutrient Regeneration Cores

- M1-Wauwinet 12 cores (shallow)
- Sedflux - 9 4 cores (shallow)
- Sedflux - 8 3 cores (deep)
- Sedflux -12 4 cores (deep)

Quaise Basin Benthic Nutrient Regeneration Cores

- Sedflux - 7 4 cores (shallow)
- Sedflux - 6 4 cores (deep)

Town Basin Benthic Nutrient Regeneration Cores

• mid-harbor 5	11 cores	(east inner region)
• Sedflux 10	4 cores	(east inner region)
• Sedflux 11	4 cores	(main basin)
• Offshore 9	12 cores	(inlet seaward of Brant Pt.)

Polpis Harbor sub-basins Benthic Nutrient Regeneration Cores

• Sedflux - 5	4 core	(East Basin)
• Polpis - 4A	12 core	(West Basin)

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

Sediment-watercolumn exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1998) for nutrients and metabolism. Upon return to the field laboratory temporarily set up adjacent the Harbor, the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and ortho-phosphate (Murphy and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-20^{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. The laboratory followed standard methods for saltwater analysis and sediment geochemistry as currently employed by the Coastal Systems Analytical Facility at SMAST.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

Watercolumn nitrogen levels are the balance of inputs from direct sources (land, rain etc), losses (denitrification, burial), regeneration (watercolumn 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 and some may be in "balance" (organic N particle settling = nitrogen release). Sediments may also take up dissolved nitrate directly from the watercolumn 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 watercolumn 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 watercolumn oxygen status. However, for the modeling of nitrogen within an embayment it is the relative balance of nitrogen input from watercolumn 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-8).

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 watercolumn 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.

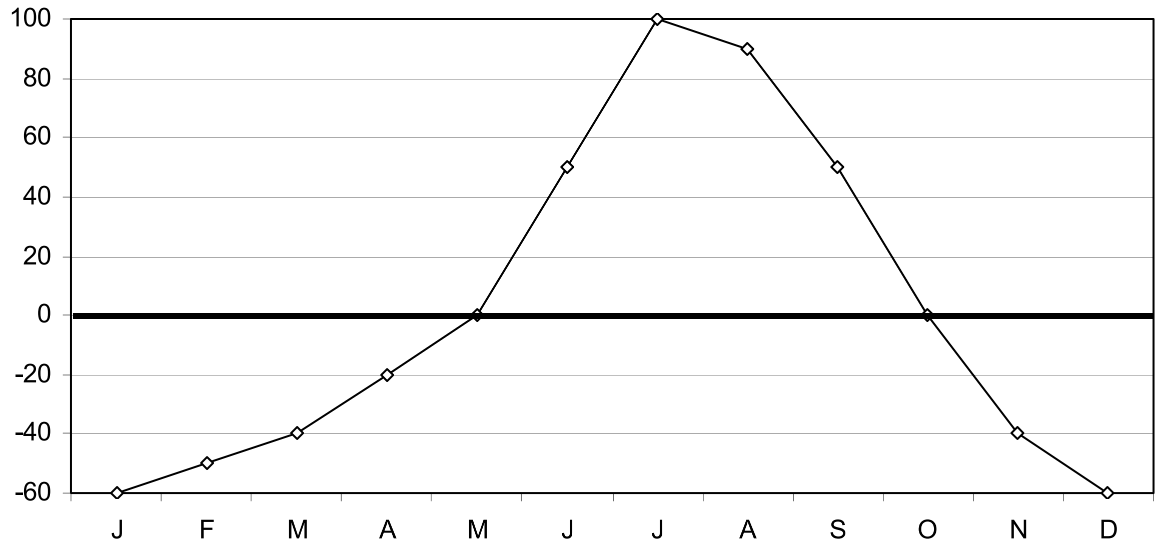


Figure IV-8. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Sediment sampling was conducted within the various sub-basins of Nantucket Harbor (e.g. Town, Quaise, Polpis Harbor and Head of the Harbor) 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. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-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). Two levels of settling were used. If the sediments were organic rich and fine grained, and the hydrodynamic data showed low tidal velocities, then a water column particle residence time of 8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins). If the sediments indicated coarse grained sediments and low organic content and high velocities, then half this 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 or uptake from the sediments within the Nantucket Harbor System were comparable to other similar embayments with similar configuration and flushing rates. Overall, sediment nitrogen release was moderate to low (66.3 to 7.7 mg N m^{-1} d^{-1}) or negative (-10.9 to -38.8 mg N m^{-1} d^{-1}) , similar to the open basin areas of the Pleasant Bay System (24.1 to -18.1 mg N m^{-1} d^{-1}) and much less than the more enclosed basins (12.3 to 138.9 mg N m^{-1} d^{-1}). These rates are also comparable to the rates for the West Falmouth Harbor Estuary (outer basin Phinneys Harbor and outer basin West Falmouth Harbor, 3 and –11 mg N m^{-1} d^{-1}, respectively). In addition, the rates fell within the wide range found for the Popponesset Bay Estuary, which ranged from 85 to - 17 mg N m^{-2} d^{-1}.

There was a clear pattern of nitrogen release throughout the Nantucket Harbor System. In the Head of the Harbor and Quaise Basins there was a clear relationship with depth, the shallow sediments showing a net uptake of nitrogen (likely associated with their oxidized nature) and the sediments from the deep basin showing a moderate net release. The pattern is positively related to the pattern of sediment organic matter content. A similar pattern is also seen in the Town Basin, where the high velocity areas to the east and within the tidal inlet show a slight net uptake and the boat basin (a net release). As expected the enclosed eastern and western basins of Polpis Harbor showed a net release, as per their organic rich nature. The Western Basin of Polpis Harbor, had a moderately high nitrogen release similar to other similar basins in southeastern Massachusetts. There was a general gradient within the System of higher rates in the depositional areas and lower or negative rates in the high velocity areas, with a general trend of declining rates of sediment nitrogen release from the innermost regions to the tidal inlet.

Net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the Nantucket Harbor System (Chapter VI) are presented in Table IV-3. Overall, the general magnitude and patterns are consistent with other estuaries. The sediments within the Nantucket Harbor System showed similar variability compared to other systems in the region and appear to be in balance with the overlying waters. Moreover, the nitrogen flux rates were consistent with the level of nitrogen loading to this system and its relatively high flushing rate.

Table IV-3. Rates of net nitrogen return from sediments to the overlying waters from within each of the component basins of the Nantucket Harbor System. 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. Shallow samples were collected at depths <8' and deep at >10'.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			Station #
	Mean	S.E.	N	
Head of the Harbor Basin				
Shallow	-38.8	1.3	16	M1, 9
Deep	50.4	1.7	7	8, 12
Quaise Basin				
Shallow	-7.9	1.4	4	7
Deep	66.3	4.0	4	6
Town Basin				
Eastern Region	-25.5	1.2	15	mid-5, 10
Boat Basin	7.7	1.0	4	11
Inlet to Brant Pt.	-10.9	1.4	12	OS9
Polpis Harbor				
East	14.6	1.9	4	5
West	65.9	1.9	12	4a

Station numbers refer to Figures IV-7 and IV-8.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes field data collection effort and the development of a hydrodynamic model for the Nantucket Harbor estuary system, on the island of Nantucket. For this system, the final calibrated model offers an understanding of water movement through the estuary, and provides the first step towards evaluating water quality, as well as a tool for later determining nitrogen loading “thresholds”. Nutrient loading data combined with measured environmental parameters within the system become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing estuarine water quality parameters, as well as determining the likely positive impacts of various alternatives for improving overall estuarine health, facilitating the understanding how pollutant loadings into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

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

Coastal embayments like the Nantucket Harbor system are the initial recipients of freshwater flows (i.e., groundwater and surfacewater) and the nutrients they carry. An embayment’s shape influences the time that nutrients are retained in them before being flushed out to adjacent open waters, and their shallow depths both decrease their ability to dilute nutrient (and pollutant) inputs and increase the secondary impacts of nutrients recycled from the sediments. Degradation of coastal waters and development are tied together through inputs of pollutants in runoff and groundwater flows, and to some extent through direct disturbance, i.e. boating, oil and chemical spills, and direct discharges from land and boats. Excess nutrients, especially nitrogen, promote phytoplankton blooms and the growth of epiphytes on eelgrass and attached algae, with adverse consequences including low oxygen, shading of submerged aquatic vegetation, and aesthetic problems.

A hydrodynamic study was performed for the Nantucket Harbor system, which is located on the island of Nantucket, south of Cape Cod. A section of a topographic map in Figure V-1 shows the general study area. The Nantucket Harbor system has many attached sub-systems, with the three main sub-divisions: 1) the main harbor basin,2) the Head of the Harbor and 3) Polpis Harbor. The entire Nantucket Harbor system has a surface coverage of 4,830 acres, including the attached sub-embayments. Polpis Harbor is the largest sub-embayment of the Harbor system, with a 280 acre coverage, including Pocomo Meadow.

Circulation in the Nantucket Harbor system is dominated by tidal exchange with Nantucket Sound. The Harbor is connected to Nantucket Sound through a broad, structured inlet. The inlet jetties are each over 3,500 ft long and are highly permeable due to their low elevation and general condition. An 80-foot-wide cut near the base of the east jetty allows the passages of boating traffic. There is little attenuation of the tide range between the inlet and Head of the

Harbor. This indicates that there is little loss of tidal energy through the system, either due to bottom friction in shallow areas or from channel restrictions, e.g., between some of the cuspate formations that are a distinguishing hallmark of the Harbor shoreline.

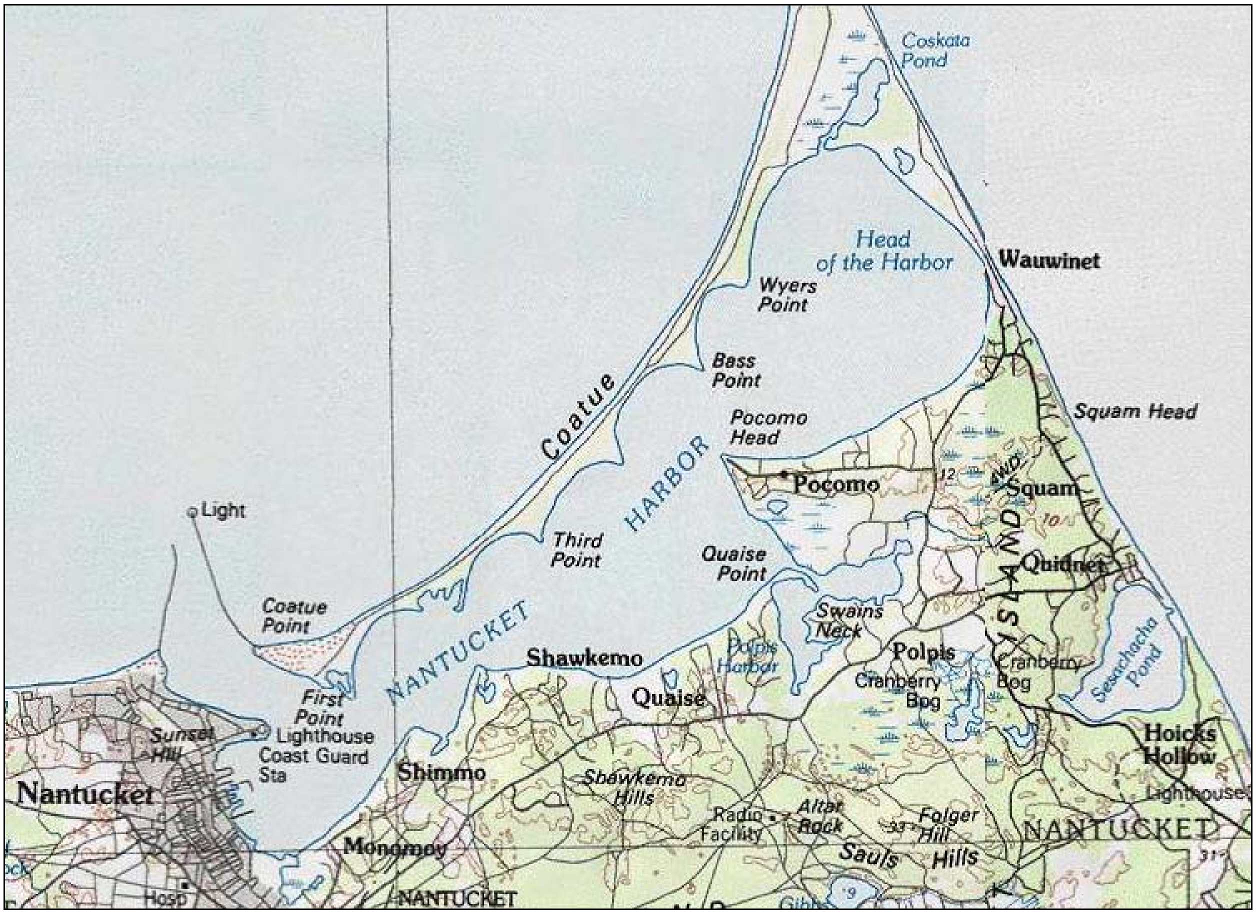


Figure V-1. Topographic map detail of Nantucket Harbor, Nantucket Island, Massachusetts.

This hydrodynamic study proceeded as two component efforts. In the first portion of the study, bathymetry, tide, and circulation velocity data were collected in order to accurately characterize the physical system, and to provide data necessary for the modeling portion of the study. The bathymetry survey of Nantucket Harbor was performed to determine the present variation of embayment and channel depths throughout the system. The recent bathymetry survey data were supplemented using historical NOAA data (NOAA, 2001) in the offshore region near the inlet. In addition to bathymetry, tides were recorded at seven locations within the Harbor system for 31 days. These tide data were necessary to run and calibrate the hydrodynamic model of the system. Finally, an Acoustic Doppler Current Profiler (ADCP) survey was completed during a single tide cycle to measure ebb and flood velocities across two channel transects. The ADCP data were used to compute system flow rates and to provide an independent means of verifying the performance of the hydrodynamic model.

A numerical hydrodynamic model of the Nantucket Harbor system was developed in the second portion of this analysis. Using the bathymetry survey data, a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data from offshore in Nantucket Sound were used to define the open boundary conditions that drive the circulation of the model at the system inlet, and data from the five TDR stations within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the real, physical system.

The calibrated computer model of the Harbor was used to compute the flushing rates of selected sub-sections. Though water quality in an embayment cannot be directly inferred by use of computed flushing rates alone, they can serve as useful indicators of embayment flushing performance relative to other areas in the same system. The ultimate utility of this hydrodynamic model is as input into a constituent transport model, where water quality constituents like nitrogen are modeled to determine the real water quality dynamics of a system.

V.2 GEOMORPHIC AND ANTHROPOGENIC EFFECTS TO THE ESTUARINE SYSTEM

From a coastal processes perspective, the northern shoreline of Nantucket is a relatively quiescent region. Although natural wave and tidal forces continue to reshape the shoreline, day-to-day conditions have limited impact on the shoreline migration and/or inlet stability. In addition, the net direction of longshore sediment transport varies along the north shore of Nantucket, primarily as a result of the variable shoreline orientation relative to the dominant wave direction. In general the littoral drift is from west-to-east along the shoreline to the west of Nantucket Harbor inlet and east-to-west along the shoreline to the east of the inlet. Evidence of this long-term sediment transport direction is a build-up of sand, resulting in historical shoreline accretion, to the west of the west jetty and to the east of the east jetty.

In contrast to the mild day-to-day conditions, typical northeast storms and infrequent hurricane events (e.g. the 1944 Hurricane and Hurricane Carol in 1954) can cause overwash of Coatue Beach. Northeast storm events (causing waves to approach the Nantucket shoreline from the east and northeast) create a sediment transport reversal from typical conditions west of the inlet; however, these transport reversals are typically short-lived and have little effect over inlet processes. Unlike many areas along the nearby Cape Cod shoreline, the Nantucket shoreline experiences similar storm surge levels from both major northeasters and hurricanes. Over the past 50 years, the largest storm surge observed in Nantucket Harbor occurred during a northeast storm in March 1956, where water elevations between 5.2 and 6.2 feet above Half Tide Level (HTL) were measured in the harbor.

V.2.1 Inlet Stabilization

Due to the quiescent wave environment and small tide range in the vicinity of the Nantucket Harbor inlet, as well as the large jetties protecting the channel, inlet migration and stability are not a concern for Nantucket Harbor. Figure V-2 shows the position of the inlet in 1890, prior to construction of jetties needed to stabilize the navigation channel. Before the jetties were constructed, significant shoaling within the inlet channel limited Nantucket Harbors use as a commercial port. Construction records indicate that rubble mound jetty construction at Nantucket Harbor was initiated in 1881 and completed in 1907. The east and west rubble-mound jetties were constructed to lengths of 6,987 and 4,955 ft, respectively. The jetties converged to a distance of approximately 1,000 ft, with the east jetty extending 800 ft seaward of the west jetty. Crown elevations of the jetties were typically +5 ft MLW, with side slopes of 1:1 (vertical: horizontal) and crest widths of 4 and 6 ft on the west and east jetties, respectively. Approximately 63,000 tons of stone were used to construct the east jetty and 59,000 tons of stone were used in the west jetty. Due to the relatively large scale and low construction elevation, jetty repairs and improvements have become commonplace for the structures. Major jetty repairs and/or improvements occurred in 1917, 1926, 1936, and 1962. The 1941 configuration of the inlet with jetties is shown in Figure V-3 and is similar to the existing configuration. Settling of the jetties since construction and/or repair allows water to flow across the structures when water levels exceed mid-tide level.

Figure V-2 A portion of the U.S.G.S. 1890 map showing Nantucket Harbor. This map depicts the condition of this inlet prior to the installation of jetties.

V.2.2 Inlet Processes and Shoreline Change Analysis

Since inlet stability is partially governed by longshore coastal sediment transport, understanding the regional long-term shoreline change and littoral movement of sand is critical for evaluating stability of Nantucket Harbor inlet. As discussed above, the observed longshore transport rates are relatively low, primarily as a result of the quiescent wave environment of Nantucket Sound. Although the amount of sand moving along the coast is small, the tidal prism through the Nantucket Harbor entrance is relatively large. Since the construction of the jetty system at the entrance, the inlet has generally reached equilibrium and the significant tidal velocities through the main channels are sufficient to inhibit shoaling.

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

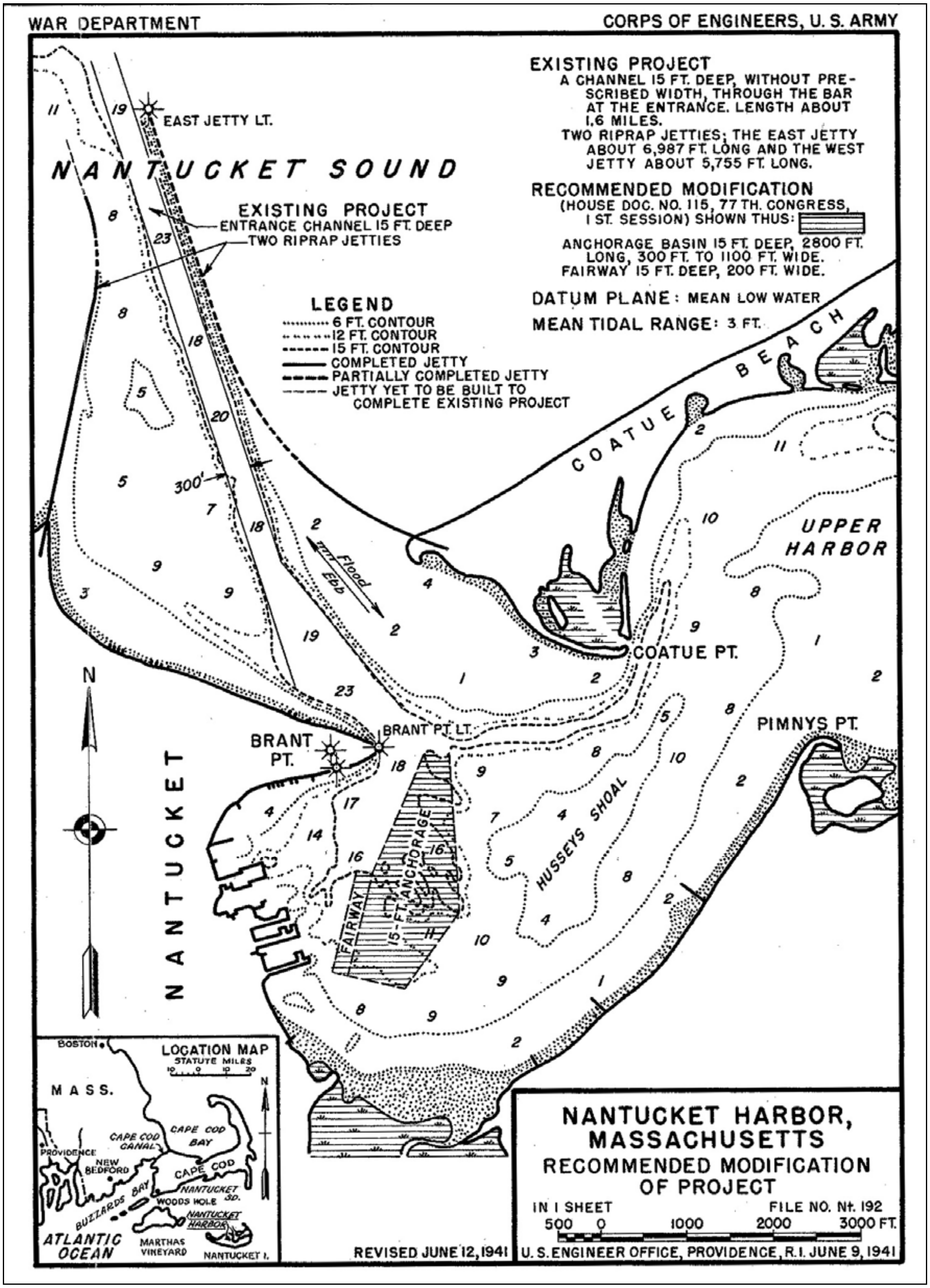


Figure V-3. Recommended navigation improvements for Nantucket Harbor, based on the 1941 U.S. Army Corps of Engineers plan.

Shoreline change was evaluated for this study during the time period from 1955 to 2003. The 1955 shoreline was digitized from the National Ocean Service (NOS) T-Sheets. The shorelines depicted on the T-sheets were created by interpreting the high-water shoreline position from controlled aerial photography. The 2003 shoreline was developed by compiling high-water shoreline position from April 2003 color orthophotographs available from MassGIS. The high-water shoreline visible on the orthophotos was digitized by hand using a line-drawing tool in ArcGIS 9.0. Although the high-water shoreline was well marked in most areas, in some instances it was difficult to discern the high-water line based on coloration and other visible features alone. For these areas, NOAA's LIDAR survey from September 25, 2000 was used to aid in the determination of shoreline position.

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

Shoreline change calculated between 1955 and 2003 (Figure V-4) shows little change along Jetties Beach, west of the entrance to Nantucket Harbor. This area shows change rates which are generally less than ±0.7 feet per year. Directly adjacent to the west jetty, an average accretion of about 2 feet per year is seen. The beach shape had stabilized following the jetty construction around 1900 and this residual accretion is due to the sheltering from the structure itself. The area immediately inside the west jetty has accreted at a rate of nearly 5 feet per year, due primarily to sand from Jetties Beach leaking over and through the west jetty. Continuing out towards Brant Point, the central portion of the beach has seen little change in the past 48 years, while the eastern tip near Brant Point Light has seen erosion of approximately 2 feet per year.

Across the harbor entrance, the shoreline has accreted along the first 4000 feet or so adjacent to the east jetty. The shoreline change rate is +4-5 feet per year immediately next to the jetty and gradually decreases to the east along Coatue Beach. This area of accretion abuts a similarly sized section of erosion which is centered opposite Second Point on the harbor side of the beach. This 4000 foot reach of shoreline has seen erosion of 2-3 feet per year. The remainder of Coatue Beach shows perhaps a slight accretion on average, but in general this reach of shoreline has seen little change.

V.2.3 Inlet Management Implications

For the tidal inlet to Nantucket Harbor, the influence of shoreline change and the related longshore sediment transport rates directly influence the stability of the existing inlet systems. According to the shoreline change analysis, the shoreline is accreting along both sides of the inlet. In addition, accretion within the inlet throat has increased beach widths at the base of the jetties within the entrance channel. Continued settling of the structures will allow shoaling to increase; however, this increase to inlet shoaling rates will be gradual. At the present time, the inlet to Nantucket Harbor provides for safe navigation as well as efficient tidal circulation.

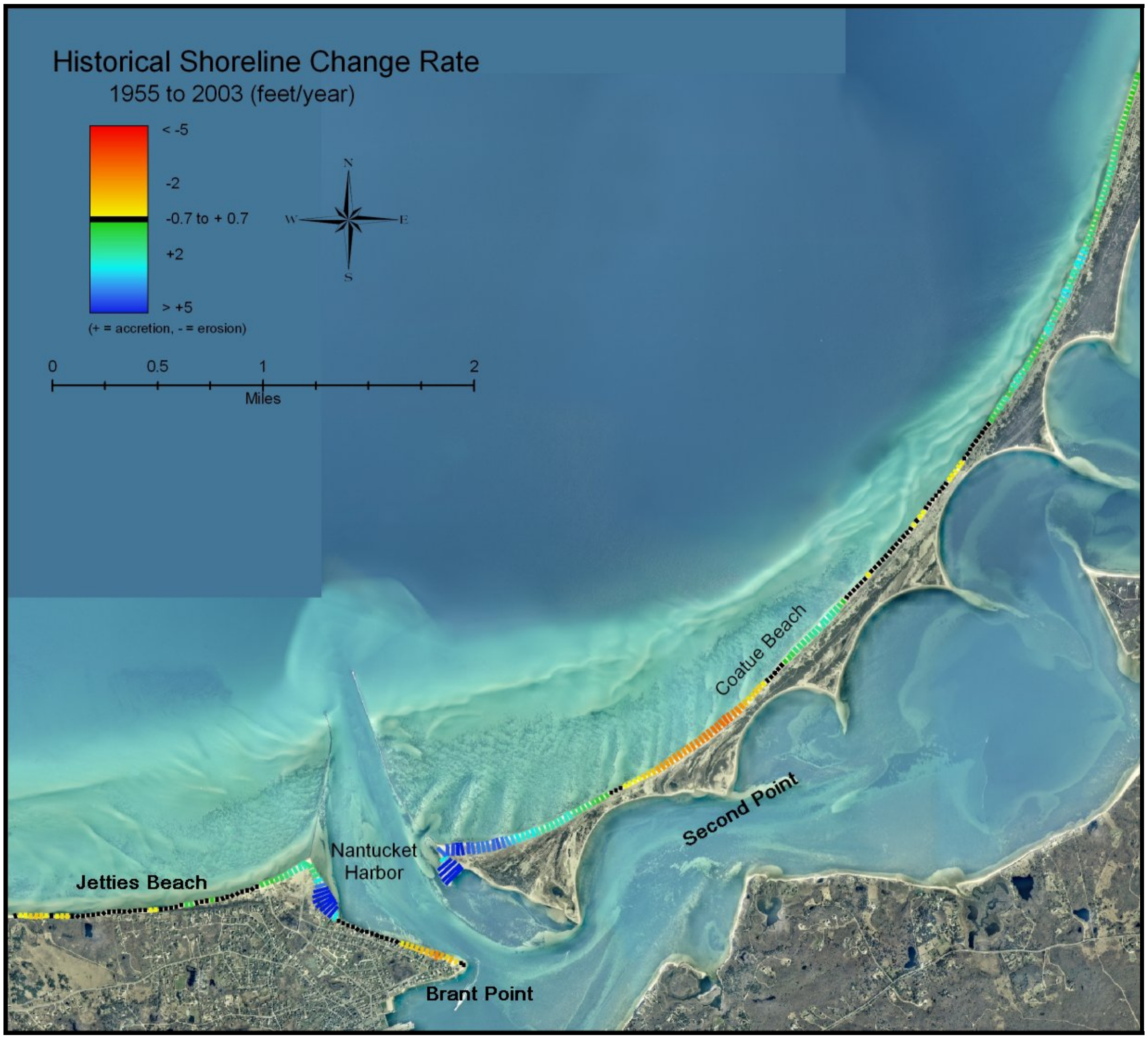


Figure V-4. Historical shoreline change rates (1955-2003) in the area of Nantucket Harbor.

V.3 DATA COLLECTION AND ANALYSIS

The field data collection portion of this study was performed to characterize the physical properties of the Nantucket Harbor estuary. Bathymetry were collected throughout the system so that it could be accurately represented in the computer hydrodynamic model and water quality model of the system. In addition to the bathymetry, tide data were also collected at six locations, to run the circulation model with real tides, and also to calibrate and verify its performance.

V.3.1 Bathymetry Data Collection

Bathymetry data in Nantucket Harbor were collected during September 2004. Supplemental offshore NOAA bathymetry were available from a 1958 survey of the Harbor vicinity. The September 2004 survey employed a bottom tracking Acoustic Doppler Current Profiler (ADCP) mounted on an inboard motor boat. Positioning data were collected using a differential GPS. The survey design included gridded transects at roughly 1000 ft spacings in along the main basin, and finer spacings at the inlet and in Polpis Harbor. Survey paths are shown in Figure V-5. The resulting bathymetric surface created by interpolating the data to a finite element mesh is shown in Figure V-6. All bathymetry was tide corrected, and referenced to the North American Vertical Datum of 1988 (NAVD 88), using survey benchmarks located in the project area.

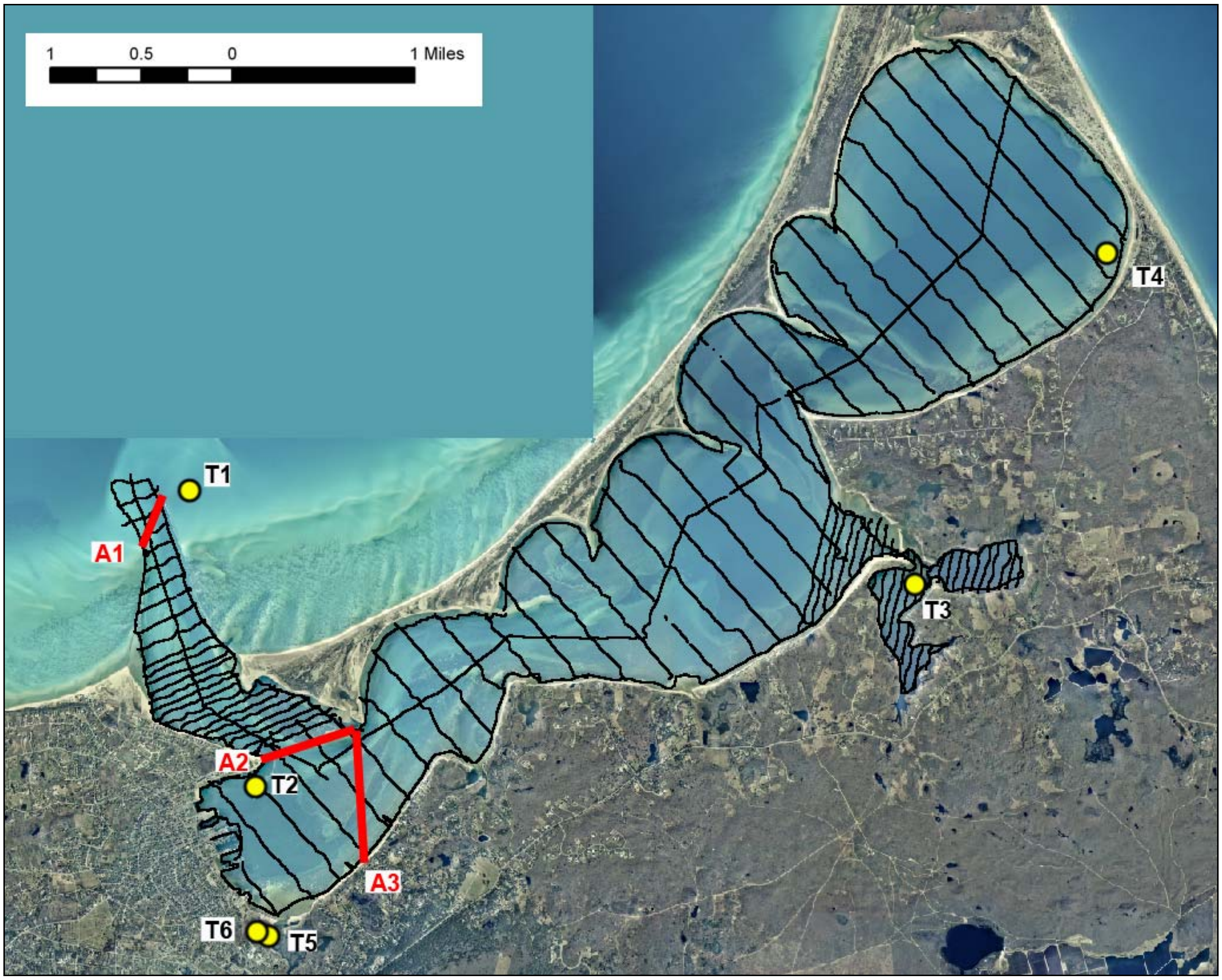


Figure V-5. Transects from the bathymetry survey of the Nantucket Harbor markers show the locations of the three tide recorders deployed for this study.

Results from the survey show that the deepest point within the Harbor is located off of Brant Point in the navigation channel, and is -33.9 ft NAVD. Other deep regions of the Harbor include the basin off of Polpis Harbor, which has a maximum depth of -28.0 feet, and the Head of the Harbor, which has a maximum depth of -25.2 feet, and an average depth of -9.8 feet. The maximum depth found in Polpis Harbor is -10.6 feet, and this basin has an average depth of -5.0 feet.

V.3.2 Tide Data Collection and Analysis

Tide data records were collected at six stations in the Nantucket Harbor estuary: 1) offshore the Harbor inlet, 2) Brant Point (at the USCG station), 3) Head of the Harbor, 4) Polpis Harbor, 5) The Creeks and 6) Consu Pond. The locations of the stations are shown in Figure V-11. The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 31-day period between August 30 and September 30, 2004. The elevation of each gauge was surveyed relative to NAVD 88. Duplicate offshore gauges were deployed to ensure data recovery, since the offshore tide record is crucial for developing the open boundary condition of the hydrodynamic model of the Nantucket Harbor system. Data from Brant Point, Polpis Harbor and the Head of the Harbor were used to calibrate the model.

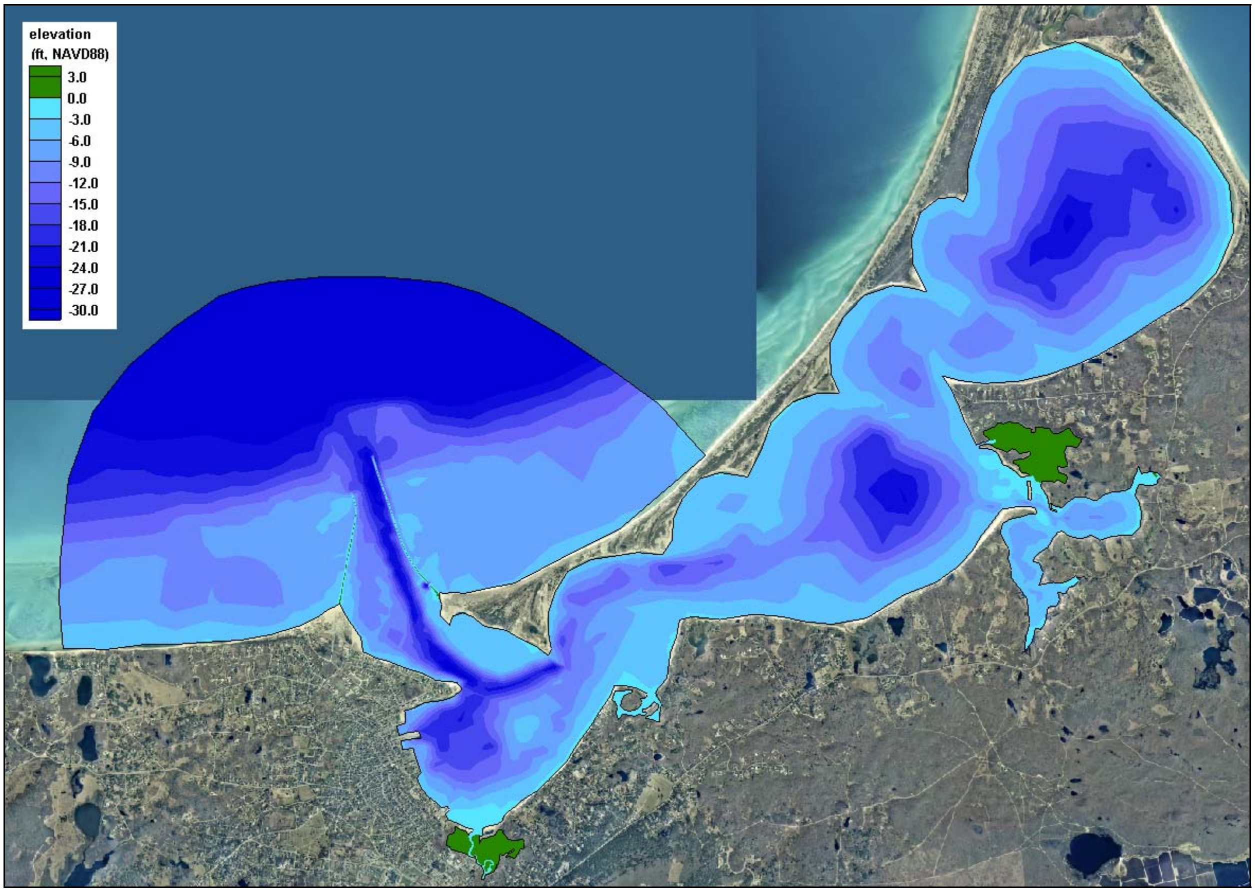


Figure V-6. Plot of interpolated finite-element grid bathymetry of the Nantucket Harbor system, shown superimposed on 2003 aerial photos of the system locale. Bathymetric contours are shown in color at three-foot intervals.

Plots of the tide data from five representative gauges are shown in Figure V-7, for the entire 31-day deployment. The spring-to-neap variation in tide can be seen in these plots. From the plot of the data from offshore Nantucket Harbor, the tide reaches its maximum spring tide range of approximately 4.0 feet around August 31, and about seven days later the neap tide range is much smaller, as small as 1.5 feet. The second spring tide should occur around September 14, the time of the new moon, but the tide range is not clearly larger than seven days earlier during the spring tide range. The causes of this odd feature of the tide in this are discussed from the results of the harmonic analysis later in this section.

A visual comparison in Figure V-8 between tide elevations at four stations in Nantucket Harbor shows that there is negligible reduction in the tide range in the upper reaches of the system. The loss of amplitude with distance from the inlet is described as tidal attenuation. Frictional mechanisms dissipate tidal flow energy, resulting in a reduction of the height of the tide. Tide attenuation is accompanied by a time delay (or phase lag) in the time of high and low tide (relative to the offshore tide), which becomes more pronounced farther into an estuary. The tide lag greatest at the Head of the Harbor, as seen in Figure V-8, where low tide occurs approximately 90 minutes after low tide in Nantucket Sound.

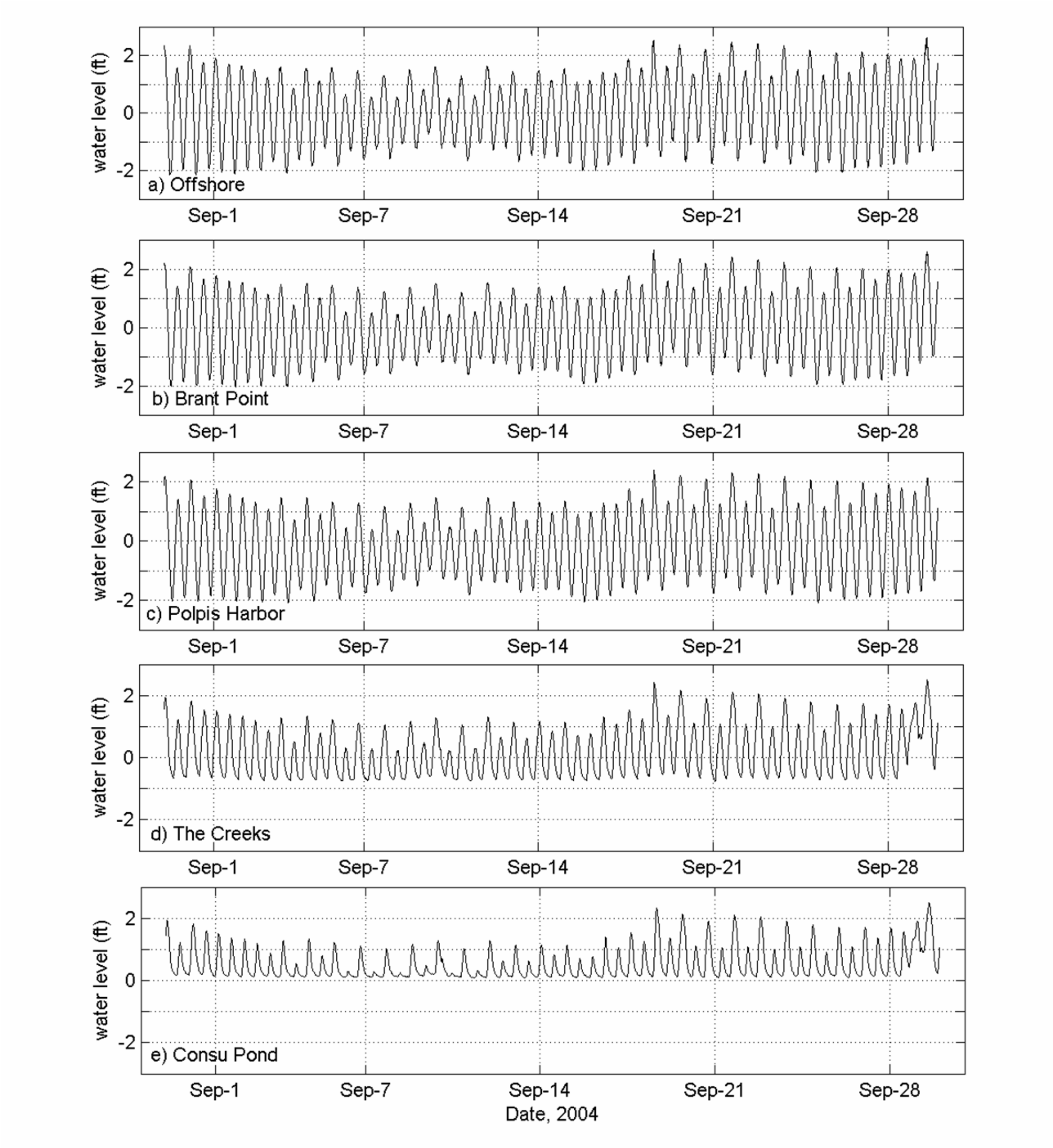


Figure V-7. Plots of observed tides for the Nantucket Harbor system, for the 31-day period between August 30 and September 30, 2004. The top plot shows tides offshore Nantucket Harbor inlet, in Nantucket Sound. Tides recorded in the Harbor at Brant Point, Polpis Harbor, The Creeks and in Consu Pond are also shown. All water levels are referenced to the **North American Vertical Datum** of 1988 (NAVD 88).

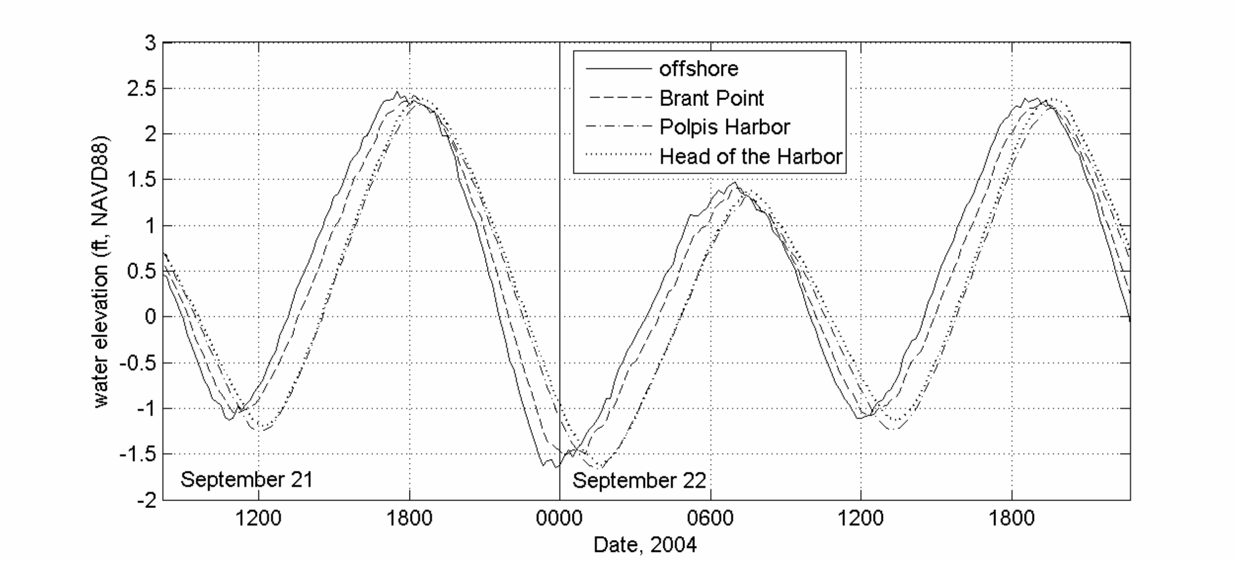


Figure V-8. Plot showing two tide cycles tides at three stations in the Nantucket Harbor system plotted together. Demonstrated in this plot is the minor frictional damping effect caused by flow restrictions at the inlets. The damping effects are seen only as a lag in time of high and low tides from Nantucket Sound. The time lag of low tide between the Sound and Prince Cove in this plot is 50 Minutes.

Standard tide datums were computed from the 31-day records. These datums are presented in Table V-1. 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 was 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. The lack of tide attenuation through the main basin of the Nantucket Harbor estuary is apparent by how there is essentially no change in the elevation of each of the datums, from Nantucket Sound to the Head of the Harbor. A larger difference is observed in the records from The Creeks and Consu Pond, which are marsh regions. The gauge from The Creeks shows an elevated MLW and MTL, compared to the Harbor, which is typical of tides in marsh creeks. The gauge from Consu Pond shows additional increases in MLW and MTL which is due to the culvert between The Creeks and Consu Pond.

The tides in Nantucket Sound are semi-diurnal, meaning that there are typically two tide cycles in a day. There is usually a small variation in the level of the two daily tides. This variation can be seen in the differences between the MHHW and MHW, as well as the MLLW and MLW levels.

A more thorough harmonic analysis of the tidal time series was 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 a quantitative assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of the system.

A harmonic analysis was performed on the time series from each gauge location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The observed astronomical tide is therefore 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-9. The amplitudes and phase of 23 known tidal constituents result from this procedure. Table V-2 presents the amplitudes of eight tidal constituents in the Nantucket Harbor system.

The M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an amplitude of 1.4 ft throughout the system. The total range of the M_2 tide is twice the amplitude, or 2.8 ft. The M_4 and M_6 tides are higher frequency harmonics of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water. The M_4 has an amplitude of 0.1 feet near the system inlet, but is reduced in Polpis Harbor and the Head of the Harbor. The M_6 has a very small amplitude in the system (less than 0.1 feet at all gauge stations). There is little change in the M_2 through the main basin of the Harbor, which is a further indication that friction losses in the system are minimal, and that Nantucket Harbor flushes very efficiently, even to its farthest reaches at the Head of the Harbor.

Table V-1. Tide datums computed from a 28-day period from the tide records collected in the Nantucket Harbor system. Datum elevations are given relative to NAVD 88.

Tide Datum	Offshore	Brant Point	Polpis Harbor	Head of the Harbor	The Creeks	Consu Pond
Maximum Tide	2.6	2.7	2.4	2.4	2.4	2.3
MHHW	1.8	1.7	1.7	1.8	1.5	1.5
MHW	1.5	1.4	1.4	1.5	1.2	1.2
MTL	-0.1	-0.1	-0.2	0.0	0.3	0.7
MLW	-1.6	-1.6	-1.7	-1.6	-0.7	0.1
MLLW	-1.8	-1.7	-1.8	-1.7	-0.7	0.1
Minimum Tide	-2.2	-2.0	-2.1	-2.1	-0.8	0.1

The other major tide constituents also show little variation across the system. The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.2 feet an 0.3 feet respectively. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, contribute significantly to the total tide signal, with amplitudes of 0.2 feet and 0.3 feet, respectively. The M_{sf} is a lunarsolar fortnightly constituent with a period of approximately 14 days, and is the result of the periodic conjunction of the sun and moon, and has an amplitude less than 0.1 ft.

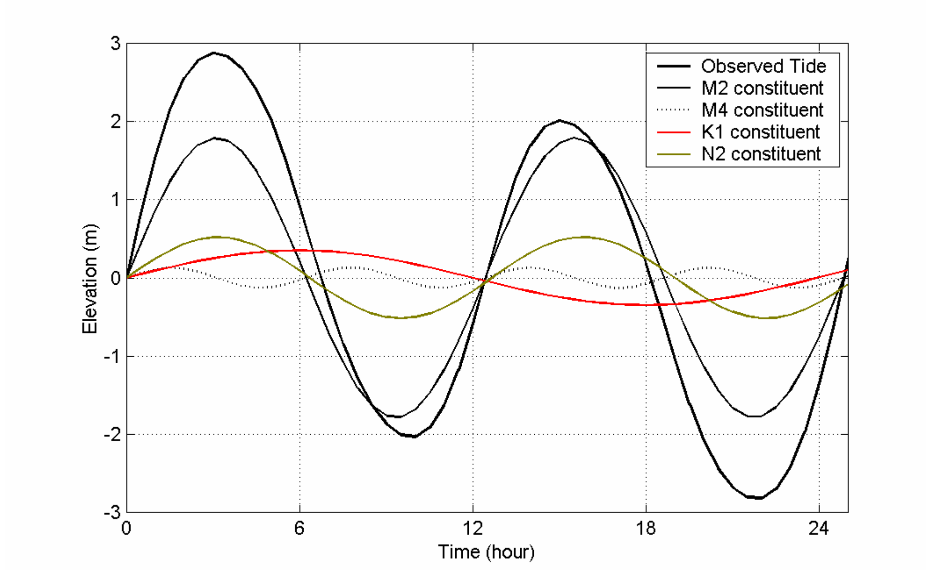


Figure V-9. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-2. Major tidal constituents determined for gauge locations in Nantucket Harbor, September 30 through October 30, 2004.

	Amplitude (feet)							
Constituent	M_2	M_4	M_6	S_2	N_2	K_1	O_1	M_{sf}
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Nantucket Sound (offshore)	1.44	0.13	0.04	0.21	0.34	0.24	0.31	0.02
Brant Point	1.37	0.09	0.04	0.19	0.31	0.24	0.30	0.02
Polpis Harbor	1.38	0.03	0.05	0.19	0.31	0.24	0.31	0.02
Head of the Harbor	1.38	0.05	0.05	0.19	0.31	0.26	0.32	0.02
The Creeks	0.88	0.12	0.04	0.10	0.20	0.23	0.26	0.08
Consu Pond	0.45	0.15	0.04	0.07	0.17	0.18	0.20	0.07

Though there is little change in constituent amplitudes across the length of the main basin of the Harbor, the phase change of the tide is easily seen from the results of the harmonic analysis. Table V-3 shows the delay of the M_2 at different points in the Nantucket Harbor system, relative to the timing of the M_2 constituent in Nantucket Sound, offshore the Coatue shoreline. The analysis of the data from the Head of the Harbor show that there is a 71 minute delay between the inlet and the farthest reach of the system. However, the greatest delay is at the Consu Pond TDR station, a sub-embayment which is closer to the inlet, but separated by the main basin of the system by marsh and a culvert. This station also showed the largest reduction of the M_2 amplitude (Table V-2). Compared to other locations instrumented in this study, Consu Pond shows the greatest tidal attenuation.

Results of the harmonic analysis provide the reason why the transition from spring to neap tide ranges is not as apparent as it is at other areas in southeastern Massachusetts (e.g., Cape Cod Bay), as discussed earlier. The cause of the mute transition between spring and neap tide ranges is the relatively large amplitudes of the N_2 (larger lunar elliptic semidiurnal constituent) and O_1 (lunar diurnal constituent) constituents. From the analysis of other tide records from around southeastern Massachusetts, the N_2 has a typical amplitude that is less than 10% of the total tide, and the O_1 is typically less than 7% of the total tide amplitude. At Nantucket Harbor however, the N_2 and O_1 have much larger amplitudes relative to the total tide, at 12% each. These constituents are slightly out of phase with the M_2 and K_1 (normally the greater contributors to the total tide amplitude), and therefore add and subtract from the total observed tide signal in cycles that are different (longer) than the 7 lunar day transition from spring to neap tides. In other areas (again, like Cape Cod Bay), the N_2 and O_1 represent a smaller percentage of the total observed tide, so there effect on the observed tide would be smaller.

Table V-3. M_2 tidal constituent phase delay (relative to Nantucket Sound) for gauge locations in the Nantucket Harbor system, determined from measured tide data.

Station	Delay (minutes)
Brant Point	23.6
Polpis Harbor	65.4
Head of the Harbor	70.5
The Creeks	60.2
Consu Pond	94.0

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 original water elevation time series for the Nantucket Harbor system is presented in Table V-4 compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 23 constituents determined by the harmonic analysis). Subtracting the tidal signal from the original elevation time series resulted with 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-10 shows the comparison of the measured tide from Nantucket Sound, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

Table V-4 shows that the variance of tidal energy was essentially equal for all stations in the main basin of the system; as should be expected given the minimal tidal attenuation to the Head of the Harbor. The analysis also shows that tides are responsible for approximately 94% of the water level changes in the Nantucket Harbor system. The remaining 6% was the result of atmospheric forcing, due to winds, or barometric pressure gradients.

Table V-4. Percentages of Tidal versus Non-Tidal Energy for stations in Nantucket Harbor, September 2004.

TDR LOCATION	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Nantucket Sound (offshore)	1.25	95.3	4.7
Brant Point	1.13	93.8	6.2
Polpis Harbor	1.13	95.0	5.0
Head of the Harbor	1.15	96.3	3.7
The Creeks	0.49	84.0	16.0
Consu Pond	0.18	74.0	26.0

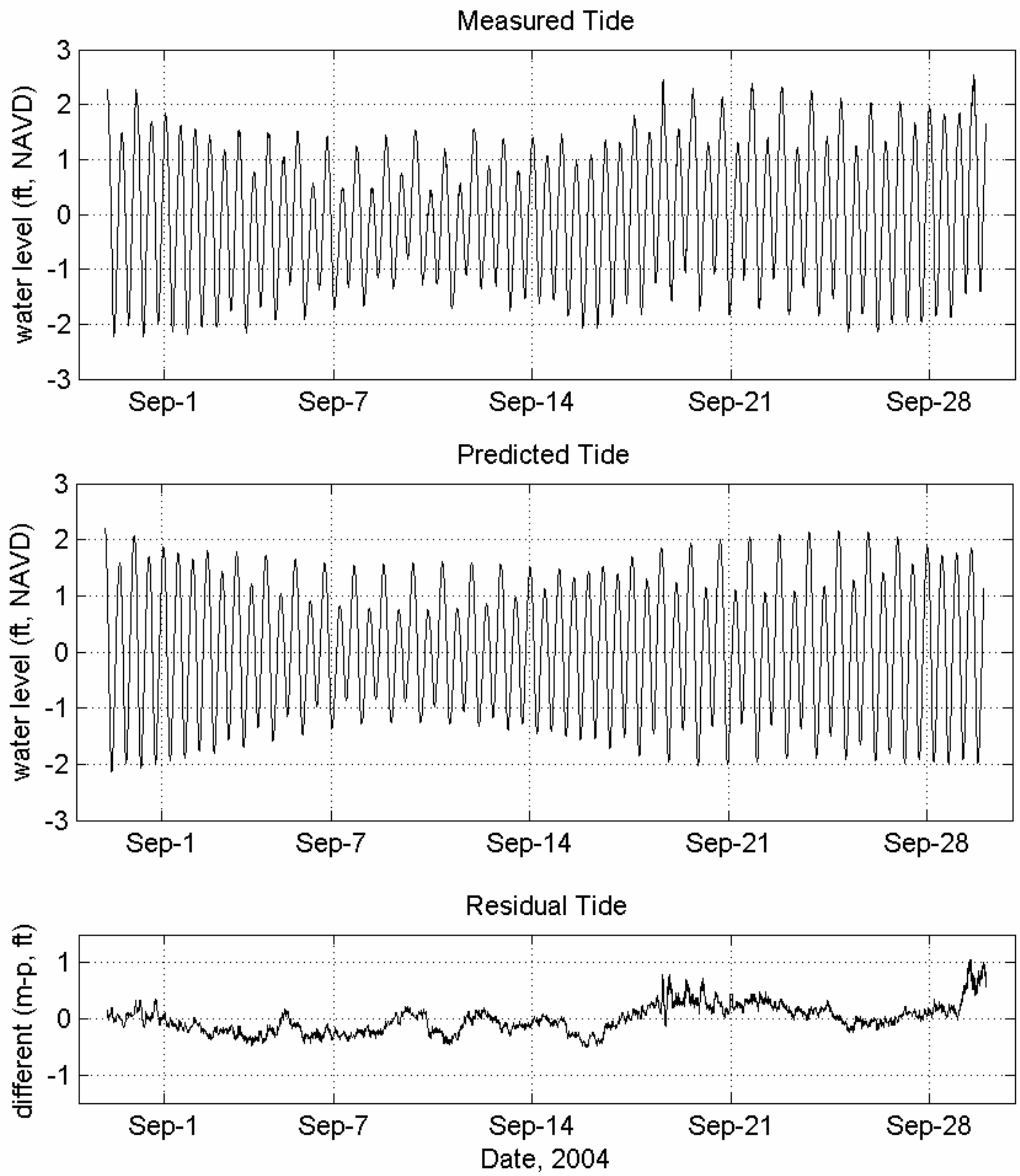


Figure V-10. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 23 individual tide constituents determine in the harmonic analysis of the Brant Point gauge data. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (r=m-p).

V.2.3 ADCP Data Analysis

Cross-channel current measurements were surveyed through a complete tidal cycle in the Nantucket Harbor system on September 23, 2004 to resolve spatial and temporal variations in tidal current patterns. The survey was designed to observe tidal flow across three transects in the system at hourly intervals. The two main transects of the survey (indicated in Figure V-5) were located 1) between Brant Point and First Point (Coatue), and 2) between first point and Shimmo (the southern Harbor shoreline). An auxiliary third transect between the tips of the inlet jetties was not followed the entire duration of the survey due to sea conditions. The data collected during this survey provided information that was necessary to model properly validate the hydrodynamic model of the Nantucket Harbor system.

Figures V-11 through V-15 show color contours of the current measurements observed during the flood and ebb tides at three of the transects. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. For example, between Brant Point and First Point, positive along-channel flow is to the south, and positive cross-channel flow is moving to west. In Figure V-11, the lower left panel shows depth-averaged currents across the channel projected onto a 1994 aerial photograph of the inlet. The lower right panel of each figure indicates the stage of the tide that the survey transect was taken by a vertical line through the water elevation curve.

Between Brant Point and First Point, maximum measured currents in the water column were between 2.6 and 3.1 ft/sec (1.5 and 1.8 knots). Maximum ebb flows in the morning of the September 23 were 32,500 ft^3/sec. In the afternoon, maximum flood flows were 41,200 ft^3/sec. Across the transect between First Point and Shimmo, maximum measured currents over the entire measured tide cycle varied less, between 2.7 and 2.8 ft/sec. During maximum ebb and flood flows, the discharge rates were 28,200 ft^3/sec and 38,100 ft^3/sec, respectively.

During maximum flood, the discharge measured at the jetty tips was 19,400 ft^3/sec, which indicates that 53% of the tidal flow enters the harbor across the jetties, as opposed to between the jetty tips. This measurement indicates that the jetties are very permeable, considering that the jetties represent 88% of the flow perimeter of the inlet, with the remaining 12% being the full width of the opening between the jetty tips. Based on the percentage of the inlet flow perimeter outlined by the jetties verses the line between the jetty tips, and that 53% of the measured flow into the Nantucket Harbor flows over the jetties, the average permeability of the Nantucket jetties (i.e., average over their entire length) is computed to be 61%. The actual permeability of the jetties is dependent upon the stage of the tide.

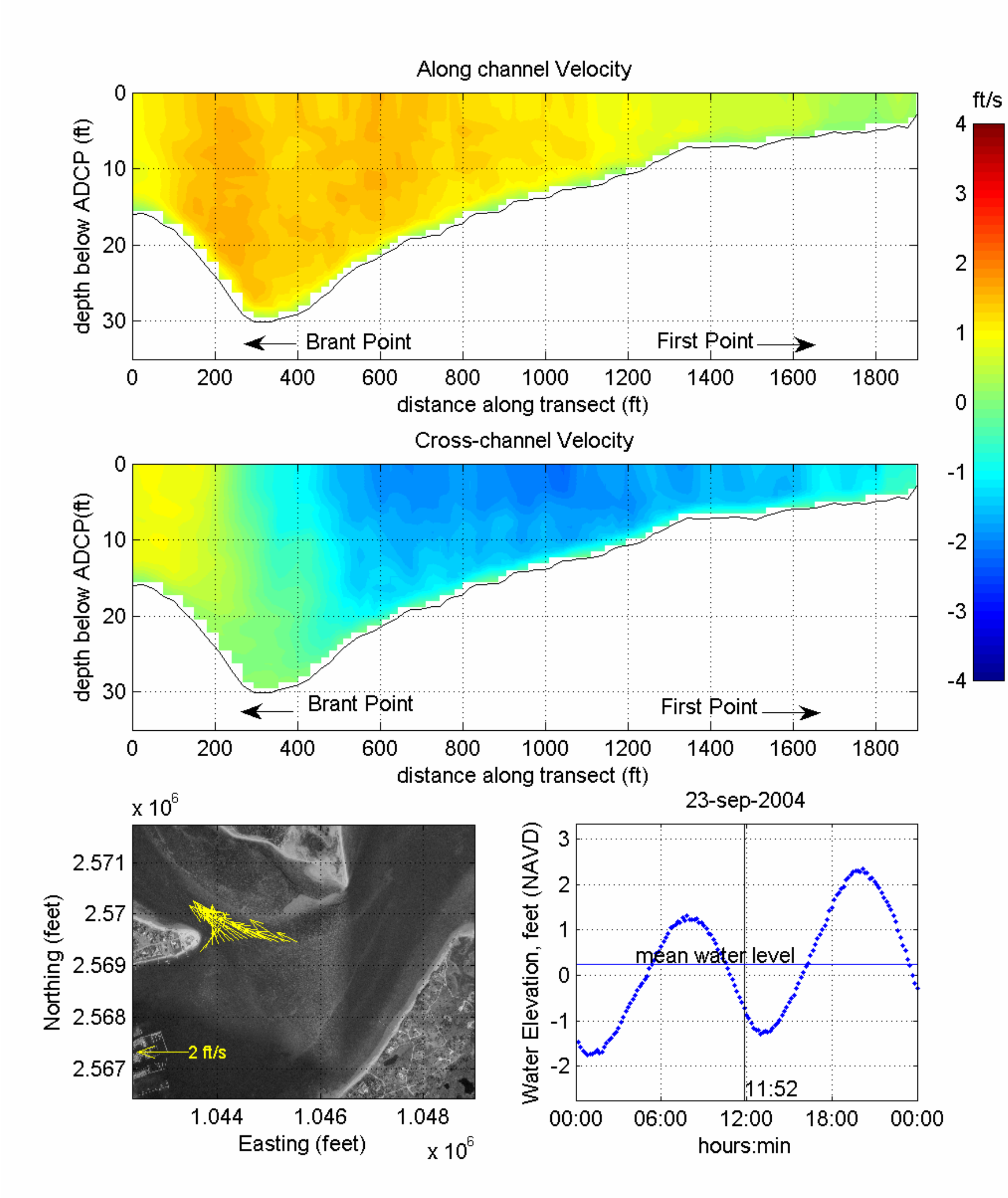


Figure V-11. Color contour plots of along-channel and cross-channel velocity components for transect line run between Brant Point and First Point, measured at 11:52 on Sep 23, 2004 during the period of maximum ebb tide currents. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Lower left plot shows scaled velocity vectors projected onto a 1994 aerial photo (MASS GIS) of the survey area. A tide plot for the survey day is also given.

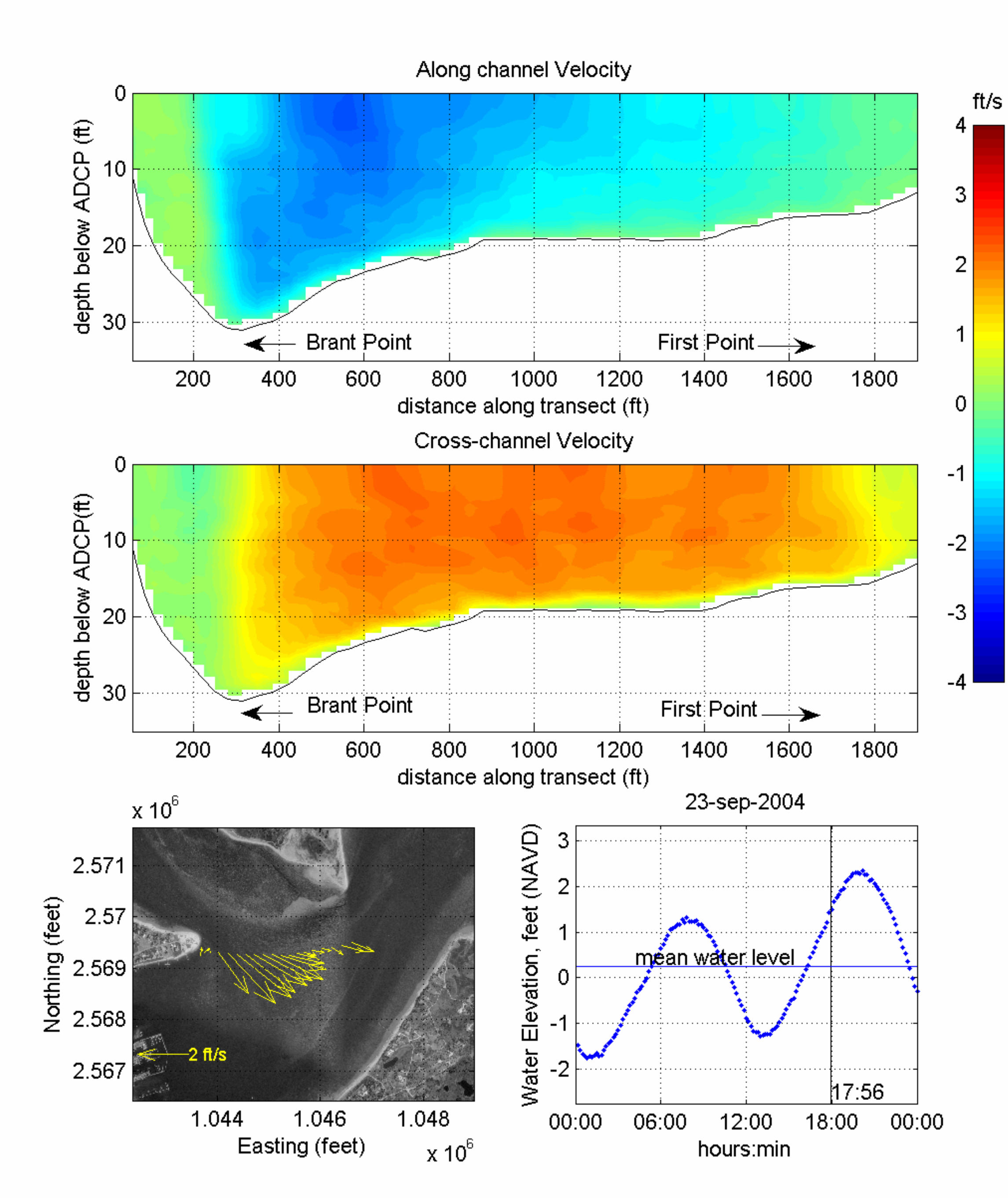


Figure V-12. Color contour plots of along-channel and cross-channel velocity components for transect line run between Brant Point and First Point, measured at 17:56 on September 23, 2004 during the period of maximum flood tide currents. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Lower left plot shows scaled velocity vectors projected onto a 1994 aerial photo (MASS GIS) of the survey area. A tide plot for the survey day is also given.

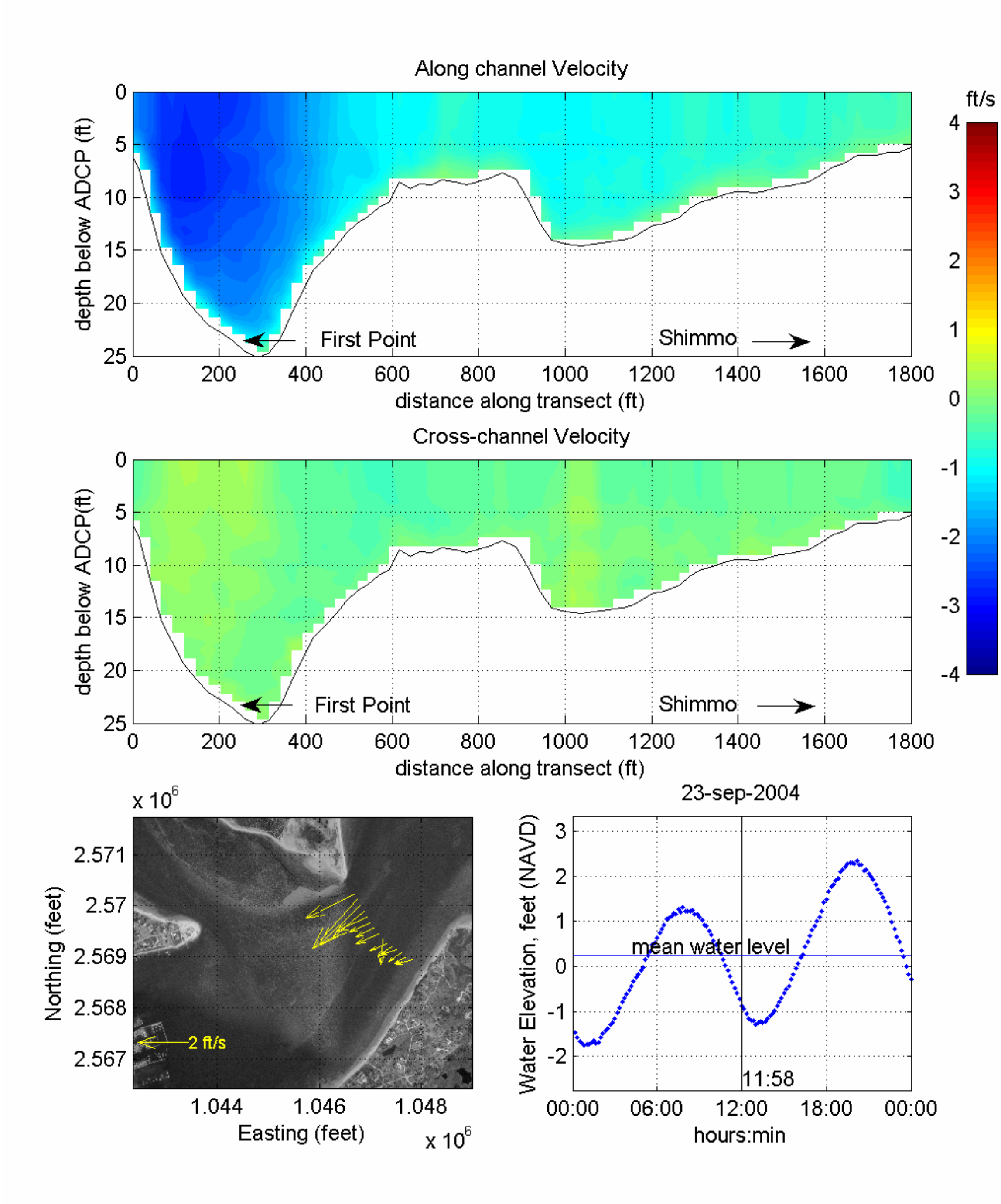


Figure V-13. Color contour plots of along-channel and cross-channel velocity components for transect line run First Point and Shimmo, measured at 11:58 on September 23, 2004 during the period of maximum ebb tide currents. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Lower left plot shows scaled velocity vectors projected onto a 1994 aerial photo (MASS GIS) of the survey area. A tide plot for the survey day is also given.

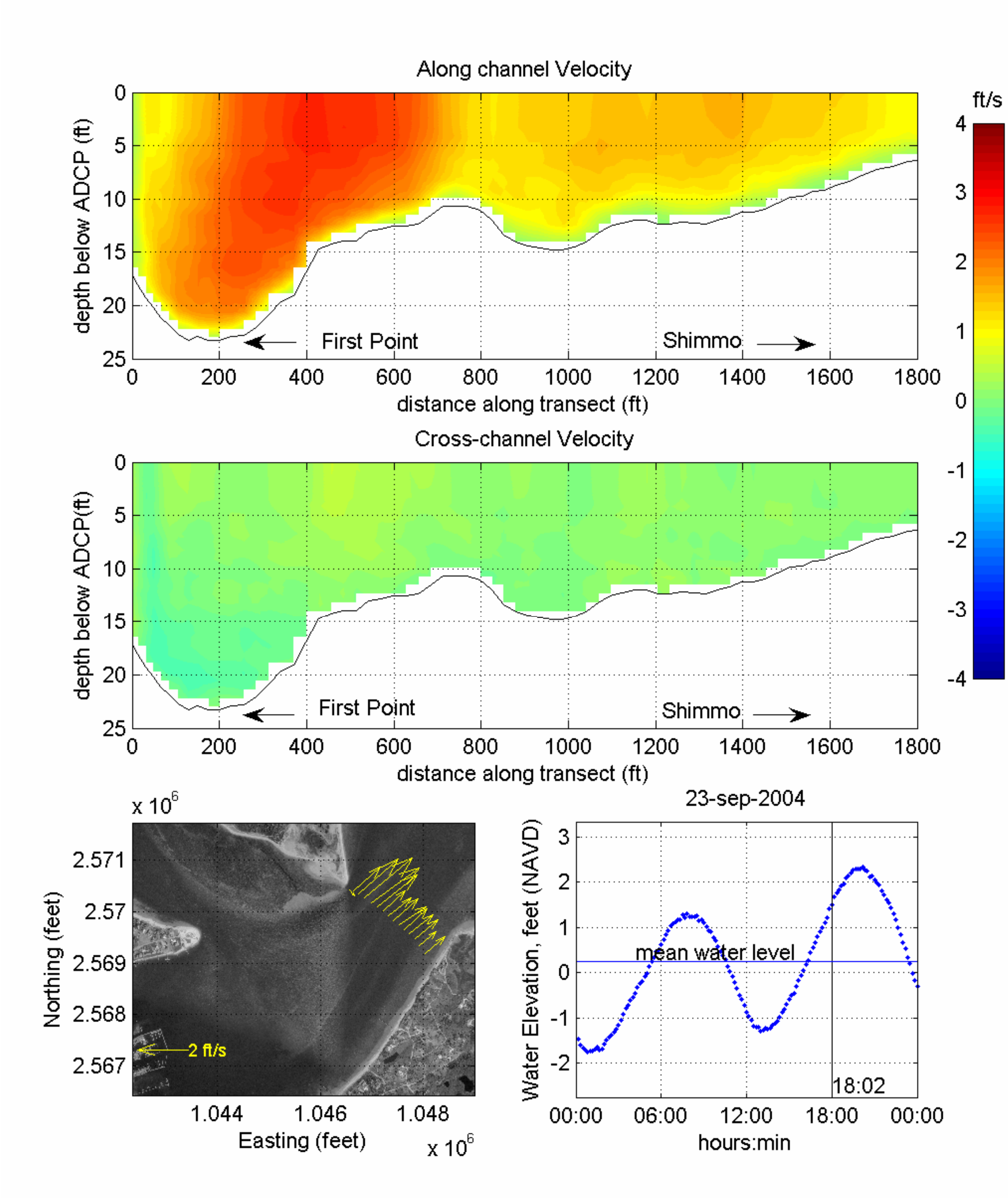


Figure V-14. Color contour plots of along-channel and cross-channel velocity components for transect line run First Point and Shimmo, measured at 18:02 on September 23, 2004 during the period of maximum flood tide currents. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Lower left plot shows scaled velocity vectors projected onto a 1994 aerial photo (MASS GIS) of the survey area. A tide plot for the survey day is also given.

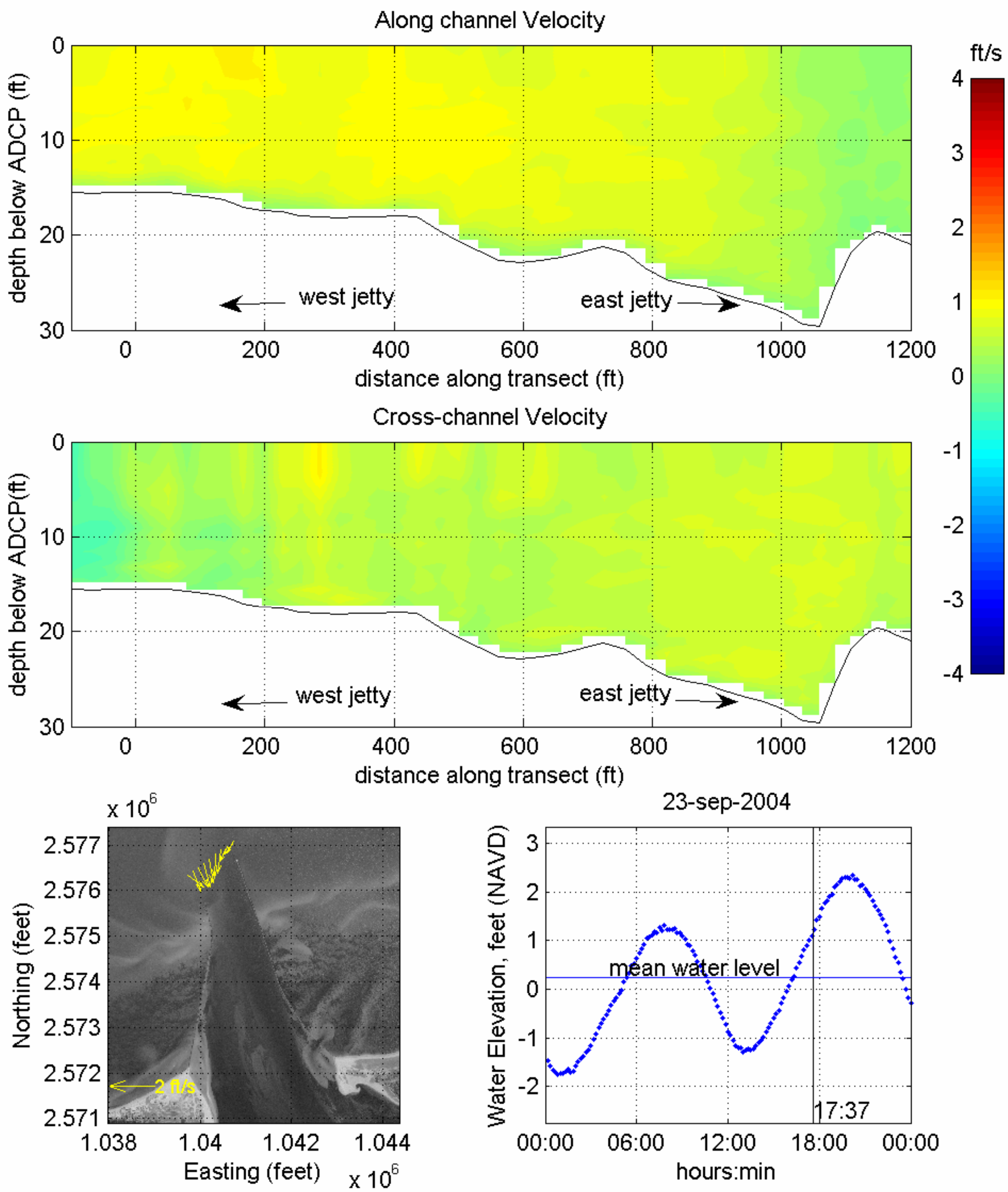


Figure V-15. Color contour plots of along-channel and cross-channel velocity components for transect line run across the jetty tips of the Harbor entrance, measured at 17:37 on September 23, 2004 during the period of maximum flood tide currents. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Lower left plot shows scaled velocity vectors projected onto a 1994 aerial photo (MASS GIS) of the survey area. A tide plot for the survey day is also given.

V.4 HYDRODYNAMIC MODELING

For modeling of Nantucket Harbor, Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in this system. 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 and the Islands, including West Falmouth Harbor, Popponesset Bay, Pleasant Bay (Howes, *et al*, 2006), Falmouth "finger" Ponds (Ramsey, *et al*, 2000), and Barnstable Harbor (Wood, *et al*, 1999), and Three Bays (Howes, *et al*, 2005).

V.4.1 Model Theory

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by a 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.4.2 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 2003 color digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the inlet of the Harbor system based on the tide gauge data collected offshore Coatue, in Nantucket Sound. 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.4.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. 2003 digital aerial orthophotos and recent bathymetry survey data were imported to SMS, and a finite element grid was created to represent the estuary. The aerial photographs were used to determine the land boundary of the system. Bathymetry data were interpolated to the developed finite element mesh of the system. The completed grid consists of 7,006 nodes, which describe 2,647 total 2-dimensional (depth averaged) quadratic elements, and covers 8,860 acres. The maximum nodal depth is -41.4 ft (NAVD 88) in the included offshore area of the grid, and -28.3 within the Harbor basin. The completed grid mesh of the Nantucket system is shown in Figure V-16, and grid bathymetry was shown previously in Figure V-6.

The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties throughout the Harbor. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Grid resolution was governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution was employed where complex flow patterns were expected. For example, smaller node spacing in main and sub-systems inlet channels was designed to provide a more detailed analysis in these regions of rapidly varying flow (e.g., the inlet channel and Polpis Harbor). Widely spaced nodes were often employed in areas where flow patterns are not likely to change dramatically, such as in the main bodies of the harbor, such as the Head of the Harbor. Appropriate implementation of wider node spacing and larger elements was used to reduce computer run time with no sacrifice of accuracy.

V.4.2.2 Boundary condition specification

Two types of boundary conditions were employed for the RMA-2 model of the Nantucket Harbor system: 1) "slip" boundaries, and 2) tidal elevation 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. Tidal boundary conditions were specified at the inlet from Nantucket Sound. TDR measurements from a gauge deployed offshore Coatue provided the required data.

The rise and fall of the tide in Nantucket Sound is the primary driving force for estuarine circulation in this system. Dynamic (time-varying) model simulations specified a new water surface elevation at the model's offshore open boundary every model time step of 10 minutes, which corresponds to the time step of the TDR data measurements.

V.4.2.3 Calibration

After developing the finite element grid, and specifying boundary conditions, the model for the Nantucket Harbor system was calibrated. The calibration procedure ensures that the model predicts accurately what was observed in nature during the field measurement program. Numerous model simulations are required (typically 10+) for an estuary model, specifying a range of friction and eddy viscosity coefficients, to calibrate the model.

Calibration of the hydrodynamic model required a close match between the modeled and measured tides in each of the sub-embayments where tides were measured (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 five lunar-day period (10 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section V.3.2. The five-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents.

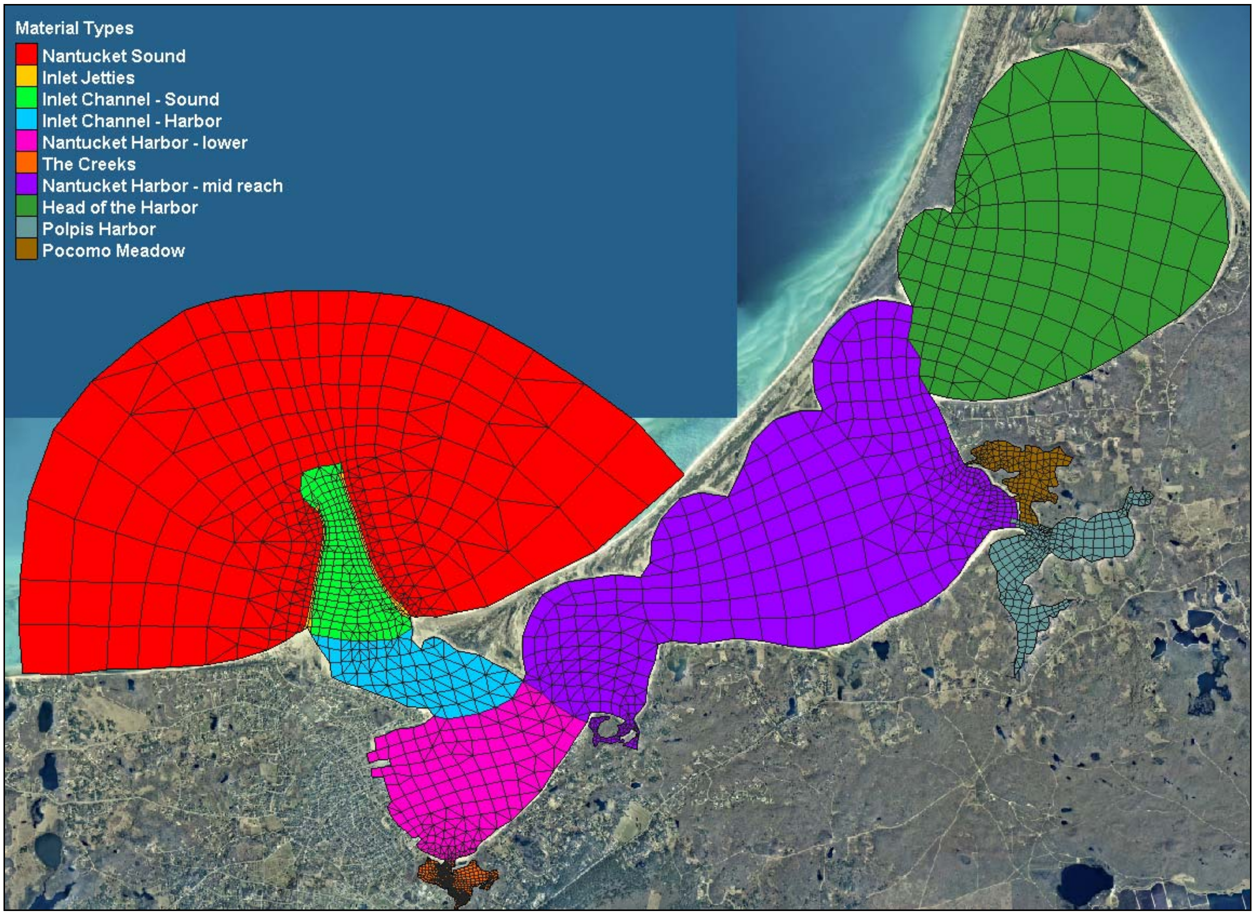


Figure V-16. Plot of hydrodynamic model grid mesh for the Nantucket Harbor estuarine system of Nantucket Island, Massachusetts. Color patterns designate the different model material types used to vary model calibration parameters and compute flushing rates.

The calibration was performed for a five-day period beginning August 30, 2004 at 0000 EDT. This representative time period included the spring tide range of conditions, where the tide range and tidal currents are greatest, and model numerical stability is often most sensitive. To provide average tidal forcing conditions for model verification and the flushing analysis, a separate time period was chosen that spanned the transition between spring and neap tide ranges (bi-weekly maximum and minimum tidal ranges, respectively).

The calibrated model was used to analyze system flow patterns and compute residence times. 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 using the entire seven-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.

V.4.2.3.1 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 coefficient values of 0.025 were specified for all element material types. This values corresponds to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) (Henderson, 1966).

During calibration, friction coefficients were incrementally changed throughout the model domain. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within the estuary system. Manning's values for different bottom types were initially selected based ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992), and 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.

Table V-5. Manning’s Roughness coefficients used in simulations of modeled sub-embayments. These embayment delineations correspond to the material type areas shown in Figure V-16.

System Embayment	Bottom Friction
Nantucket Sound	0.025
Inlet Jetties	0.100
Inlet Channel - Sound	0.025
Inlet Channel - Harbor	0.025
Nantucket Harbor - Lower	0.025
The Creeks	0.070
Nantucket Harbor - Mid Reach	0.040
Head of the Harbor	0.025
Polpis Harbor	0.025
Pomoco Meadow	0.070

V.4.2.3.2 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 other channel constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). Typically, model turbulence coefficients were set between 80 and 300 lb-sec/ft^2. In most cases, the Nantucket Harbor system was relatively insensitive to turbulent exchange coefficients. The exception was at the inlets, where higher exchange coefficient values (300 lb-sec/ft^2) were used to ensure numerical stability in these areas characterized by strong turbulent flows and large velocity magnitudes.

V.4.2.3.3 Marsh porosity processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain regions included in the model of the Nantucket Harbor system. 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.

V.4.2.3.4 Comparison of modeled tides and measured tide data

A best-fit of model predictions for the TDR deployment was achieved using the aforementioned values for friction and turbulent exchange. Figures V-17 through and V-20 illustrate the five-day calibration simulation along with a 50-hour sub-section. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

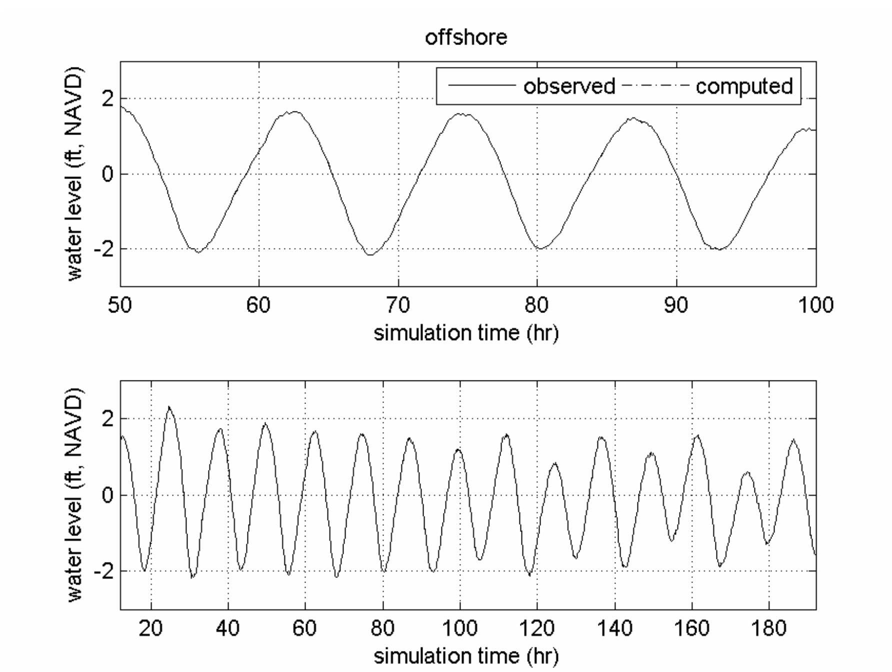


Figure V-17. Comparison of model output and measured tides for the TDR location offshore the inlet to Nantucket Harbor, in Nantucket Sound. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

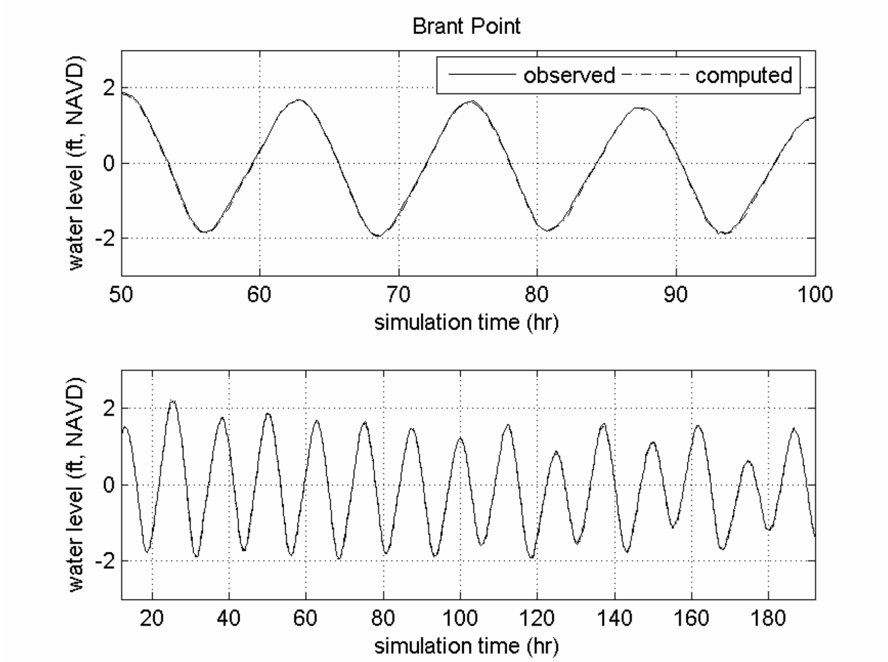


Figure V-18. Comparison of model output and measured tides for the TDR location at Brant Point. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

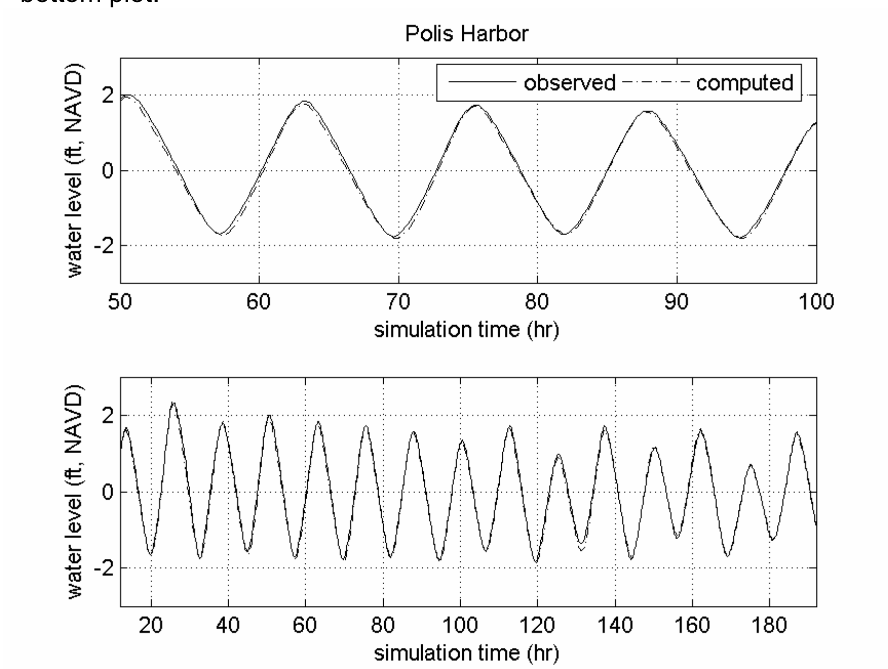


Figure V-19. Comparison of model output and measured tides for the TDR location in Polpis Harbor. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

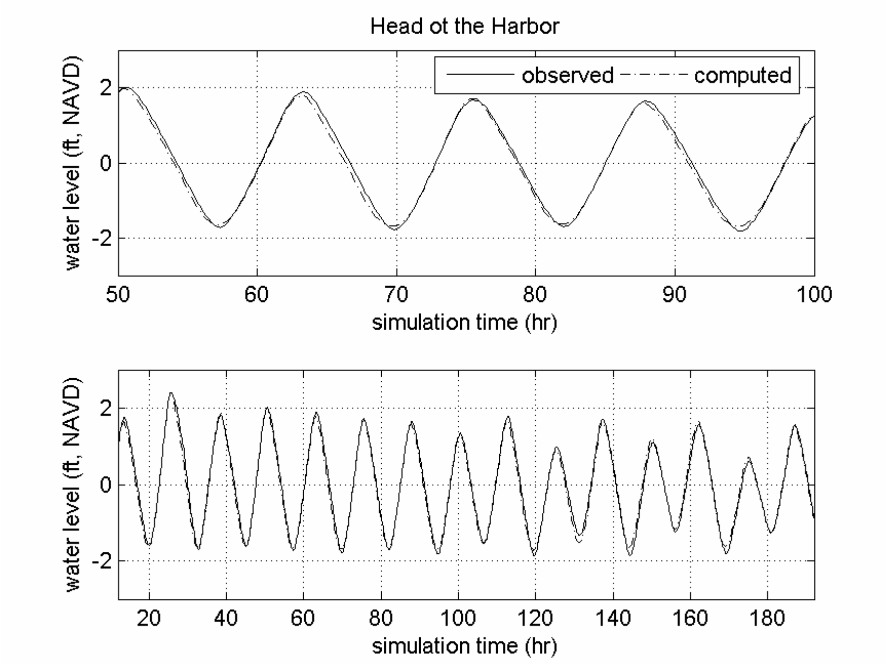


Figure V-20. Comparison of model output and measured tides for the TDR location at the Head of the Harbor. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 (principle lunar semidiurnal constituent) was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled system. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1, M_2, M_4, and M_6. Measured tidal constituent heights (H) and time lags (ϕ_{lag}) shown in Table V-6 for the calibration period differ from those in Table V-2 because constituents were computed for only the five-day section of the 31-days represented in Table V-2. Table V-6 compares tidal constituent amplitude (height) and relative phase (time) for modeled and measured tides at the TDR locations. The constituent phase shows the relative timing of each separate constituent at a particular location, and also the change (or phase lag) in timing of a single constituent at different locations in an estuary.

he constituent calibration resulted in excellent agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.01 ft, which is better than the order of accuracy of the tide gauges (±0.12 ft). Time lag errors were typically less than the time increment resolved by the model (1/6 hours or 10 minutes), indicating good agreement between the model and data.

Table V-6. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for the Nantucket Harbor system, during modeled calibration time period.

Location	Constituent Amplitude (ft)				Phase (deg)	
Model calibration run						
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound*	1.71	0.15	0.06	0.09	29.2	179.4
Brant Point	1.63	0.09	0.05	0.09	41.3	-177.5
Polpis Harbor	1.59	0.11	0.06	0.08	63.0	56.1
Head of the Harbor	1.58	0.09	0.07	0.08	61.9	68.3
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound*	1.71	0.15	0.06	0.08	30.6	-176.4
Brant Point	1.61	0.11	0.06	0.08	42.7	-170.2
Polpis Harbor	1.59	0.06	0.07	0.08	64.2	47.9
Head of the Harbor	1.60	0.09	0.07	0.11	66.7	51.4
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound*	0.00	0.00	0.00	-0.01	2.9	4.4
Brant Point	-0.02	0.02	0.01	-0.01	2.8	7.6
Polpis Harbor	0.00	-0.05	0.01	0.00	2.6	-8.5
Head of the Harbor	0.02	0.00	0.00	0.02	9.9	-17.6

*model open boundary

V.4.2.4 ADCP verification of the Nantucket Harbor system

An additional model verification check was possible by using collected ADCP velocity data to verify the performance of the Nantucket Harbor system model. Computed flow rates from the model were compared to flow rates determined using the measured velocity data. The ADCP data survey efforts are described in Section 2. For the model ADCP verification, the Harbor model was run for the period covered during the ADCP survey on September 23, 2004. Model flow rates were computed in RMA-2 at continuity lines (channel cross-sections) that correspond to two of the actual ADCP transects followed in each survey (i.e., between Brant Point and First Point, and between First Point and Shimmo). The ADCP transect between the two jetty tips was not used for the model verification because there are not sufficient measurements from this transect to make a useful comparison to model output.

Comparisons of the measured and modeled volume flow rates in the Nantucket Harbor system are shown in Figures V-21 and V-22. For each figure, the top plot shows the flow comparison, and the lower plot shows the time series of tide elevation for the same period. Each ADCP point (blue triangles shown on the plots) is a summation of flow measured along the ADCP transect. The ‘bumps’ and ‘skips’ of the flow rate curve (more evident in the model output) can be attributed to the effects of winds (i.e., atmospheric effects) on the water surface and friction across the seabed periodically retarding or accelerating the flow through the inlets, and inside the system channels. If water surface elevations changed smoothly as a sinusoid, the volume flow rate would also appear as a smooth curve. However, since the rate at which water surface elevations change does not vary smoothly, the flow rate curve is expected to show short-period fluctuations.

Data comparisons at all five ADCP transect show exceptionally good agreement with the model predictions. The calibrated model accurately describes the discharge magnitude at both lines. For all transects the R^2 correlation coefficients between data and model results are equal or greater than 0.98. The RMS error computed from each transect is less than 3,200 ft3/sec, which is 6.8% of the maximum measured discharge rate. Correlation statistics between the modeled and measured flows for each ADCP transect are presented in Table V-7.

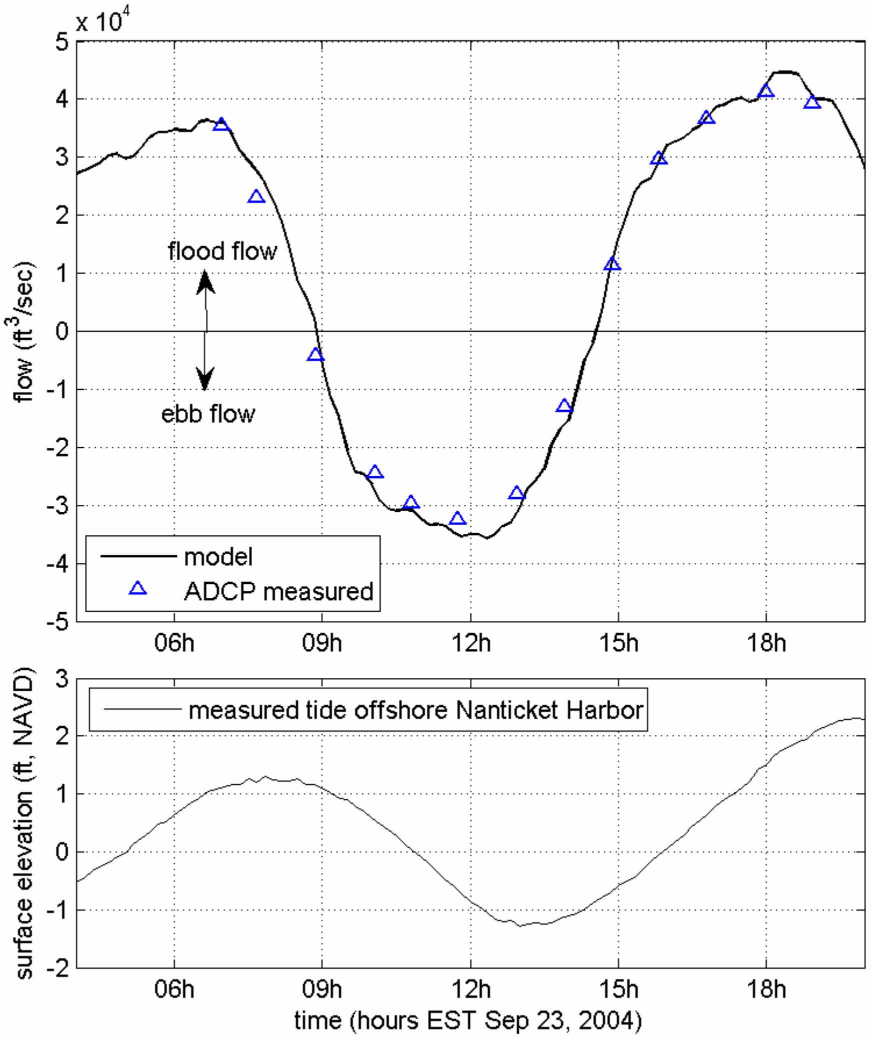


Figure V-21. Comparison of measured volume flow rates versus modeled flow rates (top plot) through the Nantucket Harbor Inlet between Brant Point and First Point, over a tidal cycle on September 23, 2004. Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore the Harbor Inlet. (R^2 =0.99, E_{RMS}=3,100 ft^3/sec).

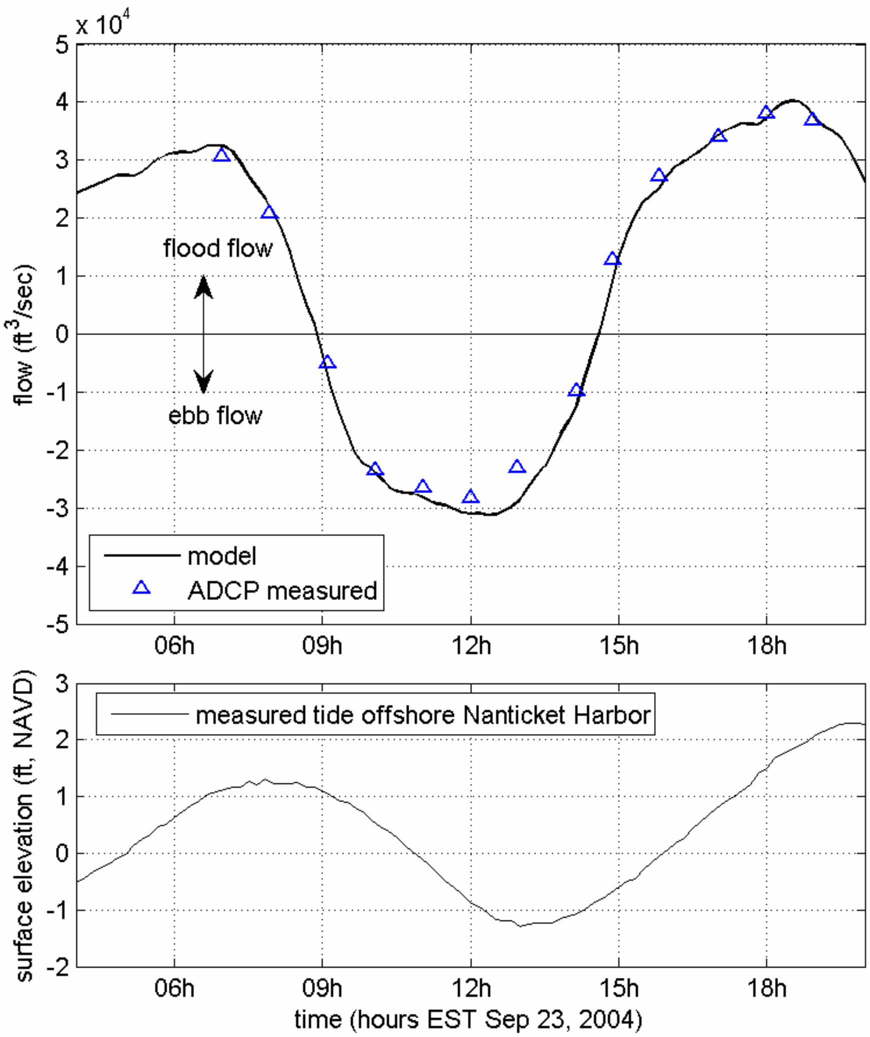


Figure V-22. Comparison of measured volume flow rates versus modeled flow rates (top plot) in Nantucket Harbor between First Point and Shimmo, over a tidal cycle on September 23, 2004. Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore the Harbor inlet. (R^2=0.98, E_{RMS}=3,200 ft^3/sec).

Table V-7. Correlation statistics between modeled and measured total flow rates at the ADCP transects used in the model verification of the Nantucket Harbor model.				
Transect	R^2 correlation	RMS error (ft^3/sec)	Max Error (ft^3/sec)	Min Error (ft^3/sec)
Brant Point to First Point	0.99	3,100	6,500	400
First Point to Shimmo	0.98	3,200	6,700	200

V.4.2.6 Model Circulation Characteristics

The final calibrated model serves as a useful tool in investigating the circulation characteristics of the Nantucket Harbor system. Using model inputs of bathymetry and tide data, current velocities and flow rates can be determined at any point in the model domain. This is a very useful feature of a hydrodynamic model, where a limited amount of collected data can be expanded to determine the physical attributes of the system in areas where no physical data record exists.

From the model run of the Harbor, maximum ebb velocities in the inlet channels are slightly larger than velocities during maximum flood. Maximum depth-averaged flood velocities in the model are approximately 2.4 feet/sec near First Point, while maximum ebb velocities are about 3.9 feet/sec. Close-up views of model output are presented in Figure V-23 and V-24, which show contours of velocity magnitude along with velocity vectors that indicate flow direction, each for a single model time-step, at the portion of the tide where maximum ebb velocities occur (in Figure V-23), and for maximum flood velocities in Figure V-24.

In addition to depth-averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs at the two system inlets is seen in the plot of flow rates in Figure V-25. Maximum flow rates occur during ebbing tides in this system. During spring tides, the maximum flood flow rates reach 50,600 ft^3/sec at the Harbor entrance between Brant Point and First Point. Maximum ebb flow rates during spring tides are slightly greater between Brant Point and First Point, about 51,900 ft^3/sec. Minimum flood flows at the Harbor Entrance during neap tides are 30,400 ft^3/sec, and minimum ebb flows during neap tides are approximately 27,500 ft^3/sec.

Another feature of the Nantucket Harbor system model is a persistent tidal eddy (or gyre) in the main commercial basin of the Harbor (near the village of Nantucket) which is set-up during flooding tides. The eddy can be seen in model output shown in Figure V-26, to the south of Brant Point. The eddy has a faint clock-wise rotation, with velocity magnitudes that are less than 0.25 ft/sec.

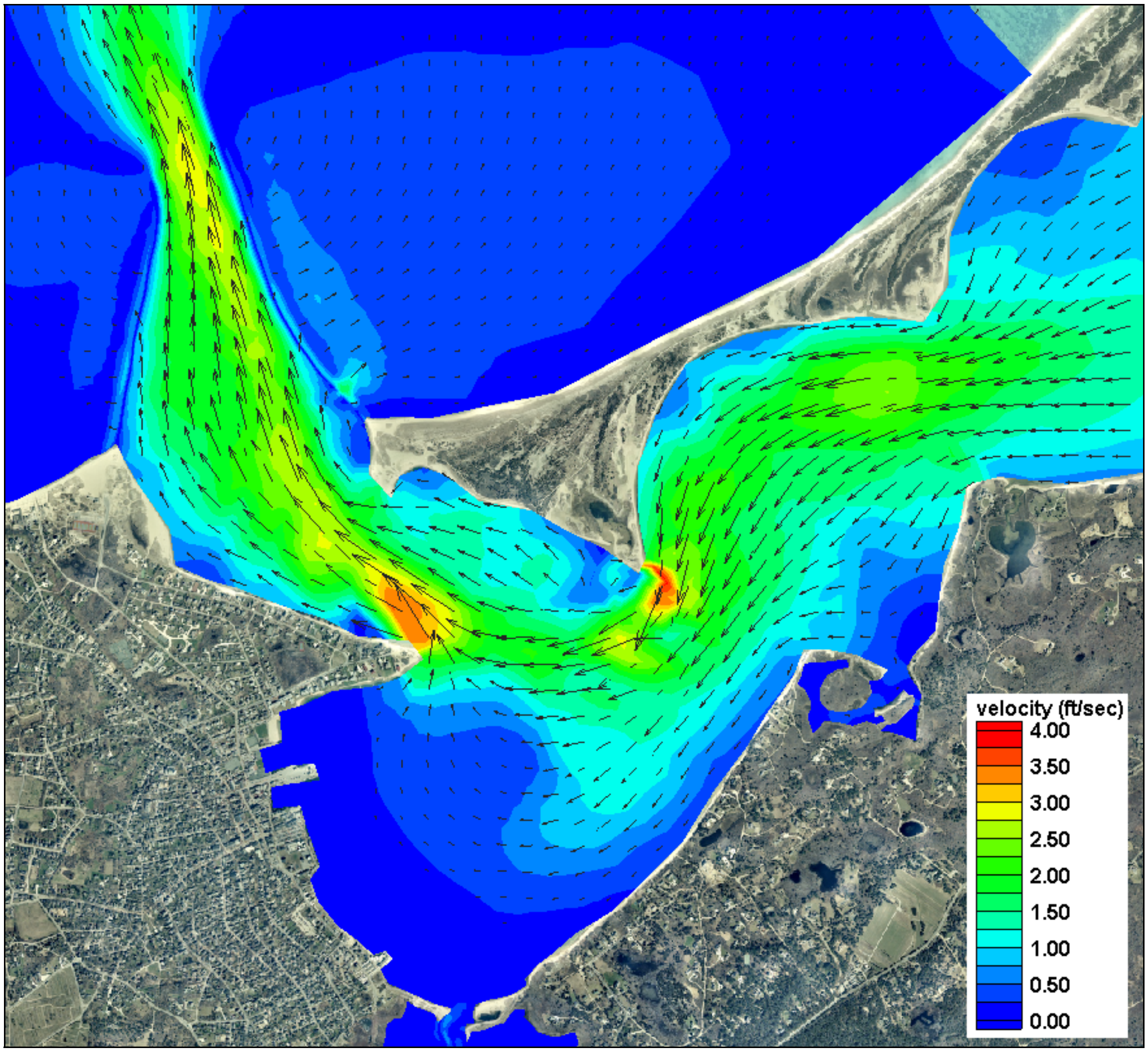


Figure V-23. Example of hydrodynamic model output for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

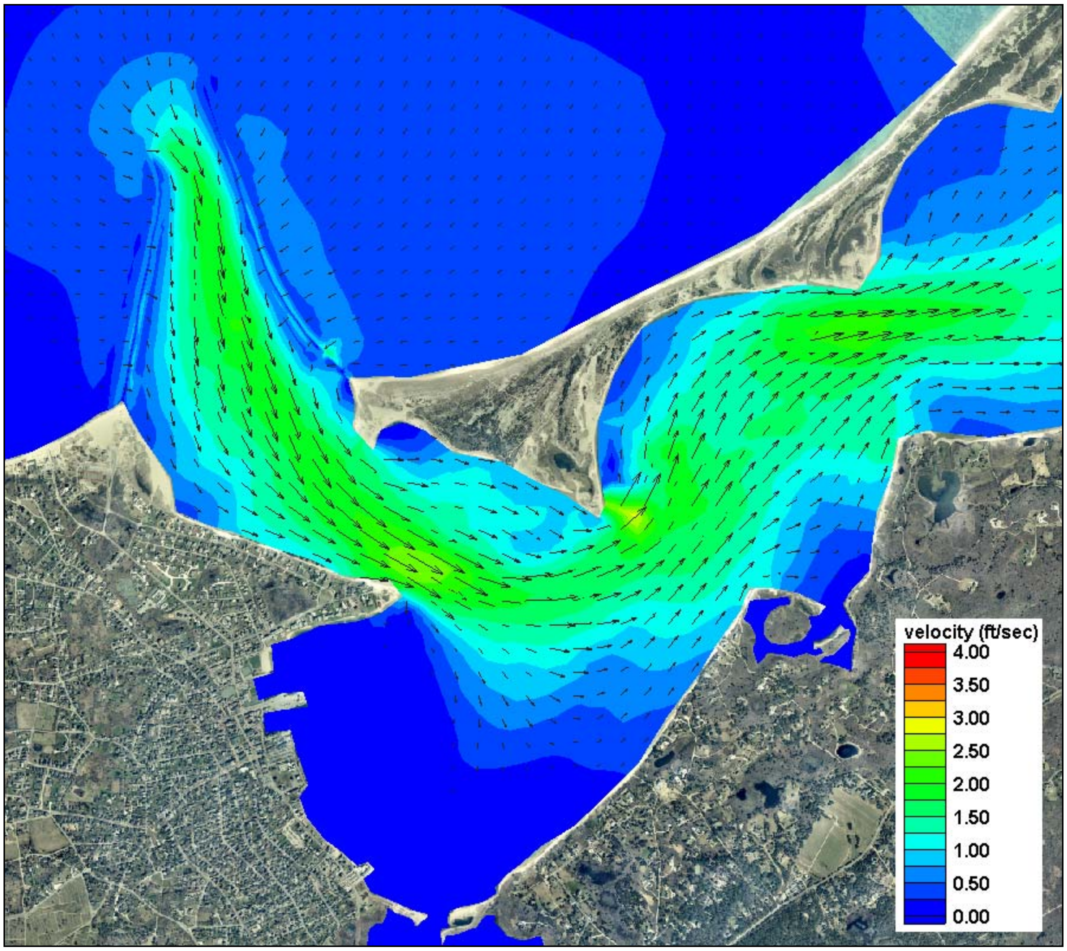


Figure V-24. Example of hydrodynamic model output for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

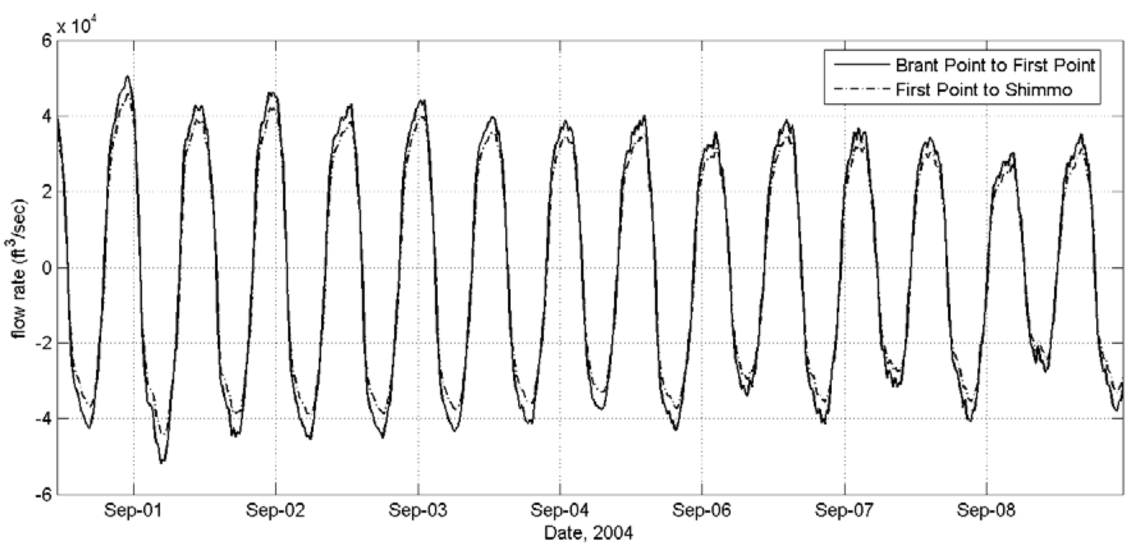


Figure V-25. Time variation of computed flow rates at two channel transects in the Nantucket Harbor system. Positive flow indicated flooding tide, while negative flow indicates ebbing tide.

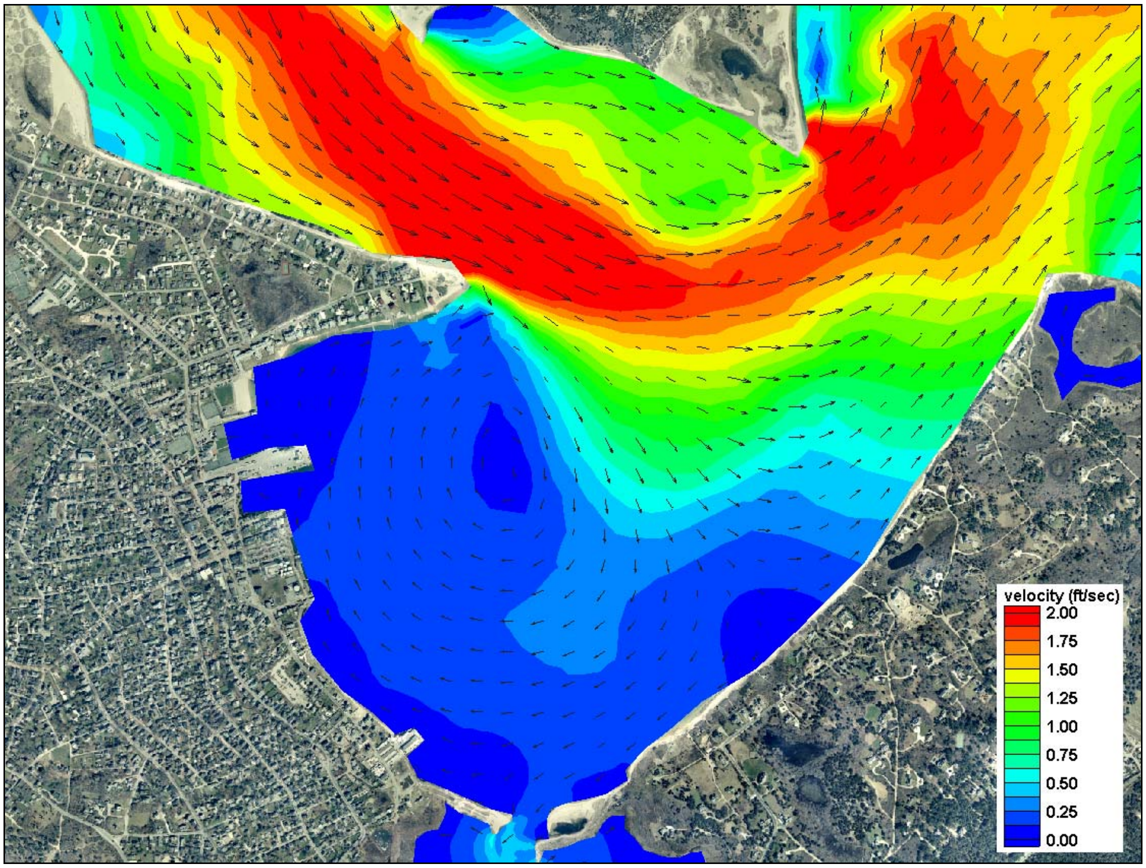


Figure V-26. Close-up of Nantucket Harbor, showing output from the hydrodynamic model at a single time step, where a recirculation eddy (or gyre) has set up on the south side of Brant Point.

V.5 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through each inlet, the primary mechanism controlling estuarine water quality within the modeled Nantucket Harbor system is tidal exchange. A rising tide offshore in Nantucket Sound 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 Nantucket Sound 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.

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 Polpis Harbor as an example, the **system residence time** is the average time required for water to migrate from Polpis Harbor, through the mid-reach of Nantucket Harbor, out through the inlet, and into Nantucket Sound, where the **local residence time** is the average time required for water to migrate from Polpis Harbor to just the main basin of Nantucket Harbor (not all the way to the Sound). 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 the Nantucket Harbor system this approach is applicable, since it assumes the main system has relatively lower quality water relative to Nantucket Sound.

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 Harbor 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 six sub-embayments within 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 include 1) the entire Nantucket Harbor system, 2) the Harbor from First Point, including Polpis Harbor and the Head of the Harbor, 3) the Head of the Harbor, 4) Polpis Harbor, 5) and The Creeks. These system divisions follow the model material type areas designated in Figure V-13. Sub-embayment mean volumes and tide prisms are presented in Table V-8.

Residence times were averaged for the tidal cycles comprising a representative 7 lunar day period (14 tide cycles), and are listed in Table V-9. The modeled time period used to compute the flushing rates started August 30, 2004, similar to the model calibration period, and included the transition from neap to spring tide conditions. The RMA-2 model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume. Since the 7 lunar day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

The computed flushing rates for the Harbor system show that as a whole, the system flushes well. A flushing time of 1.6 days for the entire estuary shows that on average, water is resident in the system less than two days. All system sub-embayments have local flushing times that are equal to or less than 2 days. The Creeks has the shortest local flushing time, because this marsh has a small mean sub-embayment volume, relative to its tide prism.

The low local residence times in all areas of the Nantucket Harbor system show that they would likely have good water quality if the system water with which it exchanges also has good water quality. For example, the water quality of Polpis Harbor would likely be good as long as the water quality of the Harbor main basin was also good. Actual water quality would still also depend upon the total nutrient load to each embayment.

Table V-8. Embayment mean volumes and average tidal prism during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Nantucket Harbor	1,984,232,000	646,811,000
Harbor from First Point	1,664,277,000	553,160,000
Head of the Harbor	752,681,000	274,938,000
Polpis Harbor	42,615,000	26,591,000
The Creeks	737,000	1,012,000

Table V-9. Computed System and Local residence times for embayments in the Nantucket Harbor system.		
Embayment	System Residence Time (days)	Local Residence Time (days)
Nantucket Harbor	1.6	1.6
Harbor from First Point	1.9	1.6
Head of the Harbor	3.7	1.4
Polpis Harbor	38.6	0.8
The Creeks	1014.7	0.4

For the smaller sub-embayments of the Harbor system, computed system residence times are typically one or two orders of magnitude longer than their corresponding local residence time. System residence times provide a qualitative measure that helps to identify the relative sensitivity of different sub-embayments to nutrient loading.

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 Nantucket Harbor system. Possible errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. 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 shoreline of Nantucket Sound typically is strong because of the effects of the local winds and tidal induced mixing within Nantucket Sound, the "strong littoral drift" assumption only will cause minor errors in residence time calculations.

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort for the Nantucket Harbor 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 nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the embayments were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated hydrodynamic model representing the transport of water within the Nantucket Harbor system. 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. The period of hydrodynamic model output used for the water quality model calibration was the 5 day period beginning August 30, 2004 0000 EST. This period corresponds to that used in the flushing analysis presented in Chapter V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic “steady state”, and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

Three primary nitrogen loads to sub-embayments are recognized in this modeling study: external loads from the watersheds, nitrogen load from direct rainfall on the embayment surface, and internal loads from the sediments. Additionally, there is a fourth load to the Nantucket Harbor system’s sub-embayments, consisting of the background concentrations of total nitrogen in the waters entering from Nantucket Sound. This load is represented as a constant concentration along the seaward boundary of the model grid.

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. The multi-year averages present the “best” comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. Typically, six years of data (collected between 1988 and 2005) were available for stations monitored by the Woods Hole Oceanographic Institute (WHOI) between 1988 and 1994, and the Town of Nantucket Marine Department between 1992 and 1994.

Table VI-1. Measured data and modeled Nitrogen concentrations for the Nantucket Harbor estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data represented in this table were collected in the summers of 1988 through 1990 and 1992 though 1994 by the Woods Hole Oceanographic Institute (WHOI), and between 1992 and 2005 by the Town of Nantucket Marine Department.

Sub-Embayment	monitoring station	MEP ID	data mean	s.d. all data	N	model min	model max	model average
Head of the Harbor - Upper	2	2	0.408	0.188	81	0.388	0.405	0.397
Head of the Harbor - Mid	Town 3	2.2	0.401	0.115	45	0.377	0.399	0.390
Head of the Harbor - Lower	2A	2.1	0.339	0.070	46	0.329	0.377	0.353
Pocomo Head	3	3	0.335	0.081	74	0.324	0.361	0.340
Quaise Basin	3A+Town 2	3.1	0.336	0.112	98	0.303	0.339	0.325
East Polpis Harbor	4+Town 6	4	0.362	0.105	107	0.354	0.371	0.361
West Polpis Harbor	4A+Town 5	4.1	0.388	0.119	100	0.358	0.385	0.371
Abrams Point	5	5	0.335	0.060	39	0.271	0.322	0.296
Monomoy	6	6	0.297	0.086	76	0.282	0.300	0.291
Mooring Area	7+Town 1,1A	7	0.326	0.106	123	0.276	0.291	0.285
Nantucket Sound	OS+Town 4	7.1	0.239	0.041	41	-	-	-

VI.2 MODEL DESCRIPTION AND APPLICATION

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of nitrogen loading in the Nantucket Harbor estuarine system. 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 Nantucket Harbor. 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. The MEP Technical Team has utilized this model in water quality studies of other Cape Cod embayments, including systems other Massachusetts estuarine systems such as Falmouth (Howes *et al*., 2005); Mashpee, MA (Howes *et al*., 2004) and Chatham, MA (Howes *et al*., 2003).

The overall approach involves modeling total nitrogen as a non-conservative constituent, where bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. This modeling represents summertime conditions, when algal growth is at its maximum. Total nitrogen modeling is based upon various data collection efforts and analyses presented in previous sections of this report. Nitrogen loading information was derived from the Cape Cod Commission watershed loading analysis (using watersheds delineated originally by the USGS and modified by WHOI), as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements were utilized as model boundaries and as calibration data. Hydrodynamic model output (discussed in Section V) provided the remaining information (tides, currents, and bathymetry) needed to parameterize the water quality model of the Nantucket Harbor system.

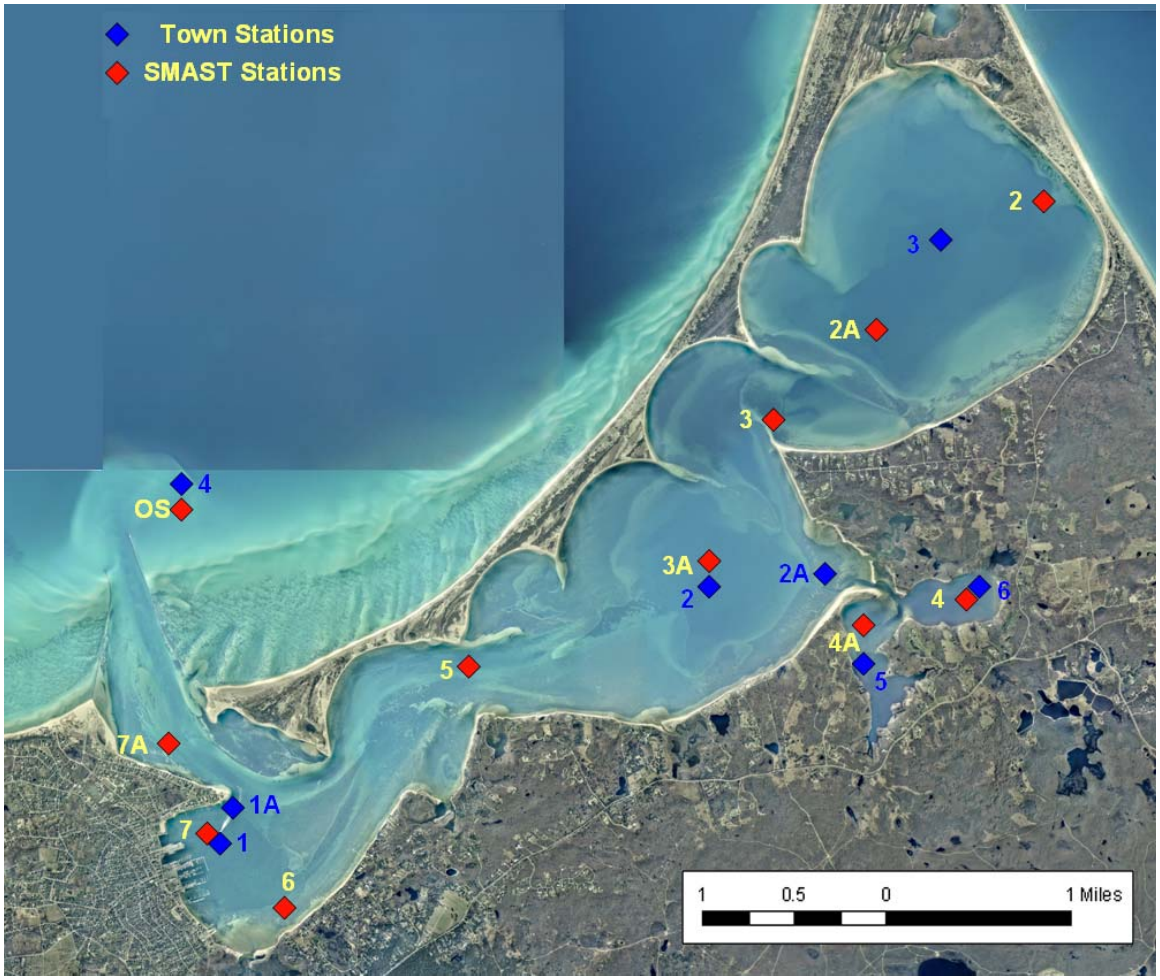


Figure VI-1. Estuarine water quality monitoring station locations in the Nantucket Harbor estuary system. Station labels correspond to those provided in Table VI-1.

VI.2.1 Model Formulation

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_x and D_y are the model dispersion coefficients in the x and y directions; and σ is the constituent source/sink term. Since the model utilizes input from the RMA-2 model, a similar implicit solution technique is employed for the RMA-4 model.

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

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

VI.2.2 Water Quality Model Setup

Required inputs to the RMA-4 model include a computational mesh, computed water elevations and velocities at all nodes of the mesh, constituent mass loading, and spatially varying values of the dispersion coefficient. Because the RMA-4 model is part of a suite of integrated computer models, the finite-element meshes and the resulting hydrodynamic simulations previously developed for Nantucket Harbor also were used for the water quality constituent modeling portion of this study.

For each model, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 7 tidal-day (174 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the Nantucket Harbor model.

VI.2.3 Boundary Condition Specification

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

The loadings used to model present conditions in the Nantucket Harbor system 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 (excluding marsh coverages, when present), resulting in a total flux for each embayment (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. For some areas of Nantucket Harbor (i.e., Head of the Harbor and the Town Basin), the net benthic flux is negative which indicates a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in the Nantucket Sound region offshore the Harbor was set at 0.267 mg/L, based on SMAST data collected during nine summers between 1988 and 2000.

Table VI-2. Sub-embayment and surface water loads used for total nitrogen modeling of the Nantucket Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions** for the listed sub-embayments.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Head of the Harbor	1.858	22.239	-17.211
Polpis Harbor	3.529	2.190	27.441
Quaise Basin	2.123	20.126	43.896
Town Basin	15.901	13.888	-2.793
System Total	23.411	58.443	51.333

VI.2.4 Model Calibration

Calibration of the total nitrogen model of Nantucket Harbor proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (*E*) values were varied through the modeled system by setting different values of *E* for each grid material type, as designated in Section V. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent estuarine embayments encircling Nantucket Sound require values of *E* that are lower compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979). Observed values of *E* in these calmer areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of *E* used in each sub-embayment of the modeled system are presented in Table VI-3. These values were used to develop the "best-fit" total nitrogen model calibration. For the case of TN modeling, "best fit" can be defined as minimizing the error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

Comparisons between calibrated model output and measured nitrogen concentrations are shown in plots presented in Figures VI-2 and VI-3. In these plots, means of the water column data and a range of two standard deviations of the annual means at each individual station are plotted against the modeled maximum, mean, and minimum concentrations output from the model at locations which corresponds to the SMAST monitoring stations.

For model calibration, the mid-point between maximum modeled TN and average modeled TN was compared to mean measured TN data values, at each water-quality monitoring station. The calibration target would fall between the modeled mean and maximum TN because the monitoring data are collected, as a rule, during mid ebb tide.

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

Embayment Division	E m^2/sec
Nantucket Sound	5.0
Harbor Jetties	5.0
Jetty Channel	5.0
Inlet Channel	5.0
Town Basin	1.0
The Creeks	5.0
Quaise Basin	10.0
Head of the Harbor	2.0
Polpis Harbor	15.0
Pocomo Meadow	5.0

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for each system. Computed root mean squared (rms) error is less than 0.02 mg/L, which demonstrates the exceptional fit between modeled and measured data for this system.

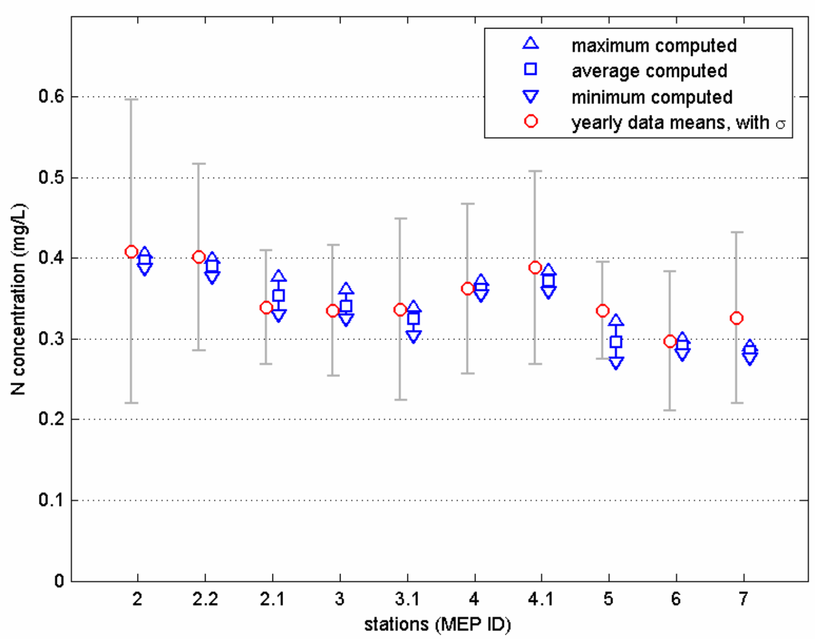


Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Nantucket Harbor system. Station labels correspond with the MEP IDs provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset

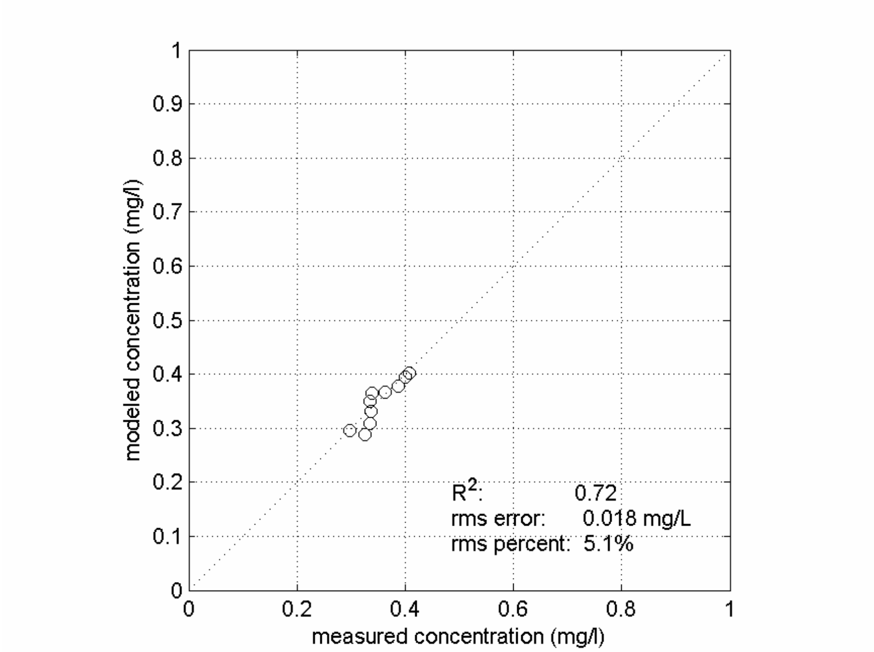


Figure VI-3. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are also presented.

A contour plot of calibrated model output is shown in Figures VI-4. In this figure, color contours indicate nitrogen concentrations throughout the model domain. The output in these figures show average total nitrogen concentrations, computed using the full 7-tidal-day model simulation output period.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Nantucket Harbor system using salinity data collected at the same stations as the nitrogen data. The only required inputs into the RMA4 salinity model of the system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, and groundwater inputs. The open boundary salinity was set at 31.9 ppt. Groundwater input salinities were set at 0 ppt. Groundwater inputs used for each model were 3.04 ft^3/sec (7,430 m^3/day) for the Head of the Harbor watershed, 8.33 ft^3/sec (20,390 m^3/day) for Polpis Harbor, 4.39 ft^3/sec (10,750 m^3/day) for the Quaise basin and 9.23 ft^3/sec (61,150 m^3/day) for the town harbor basin. Groundwater flows were distributed evenly in the model through the use of several 1-D element input points positioned along the model's land boundary.

Comparisons of modeled and measured salinities are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. The rms error of the model is less than 0.7 ppt. The model output shows the same trend of the measured data, where there is only a slight salinity gradient between the Head of the Harbor and the inlet to the system. This is because tidal exchange rate (39,353,000 m^3/day) is two orders of magnitude larger than the groundwater recharge rate (100,000 m^3/day) of the entire Harbor system.

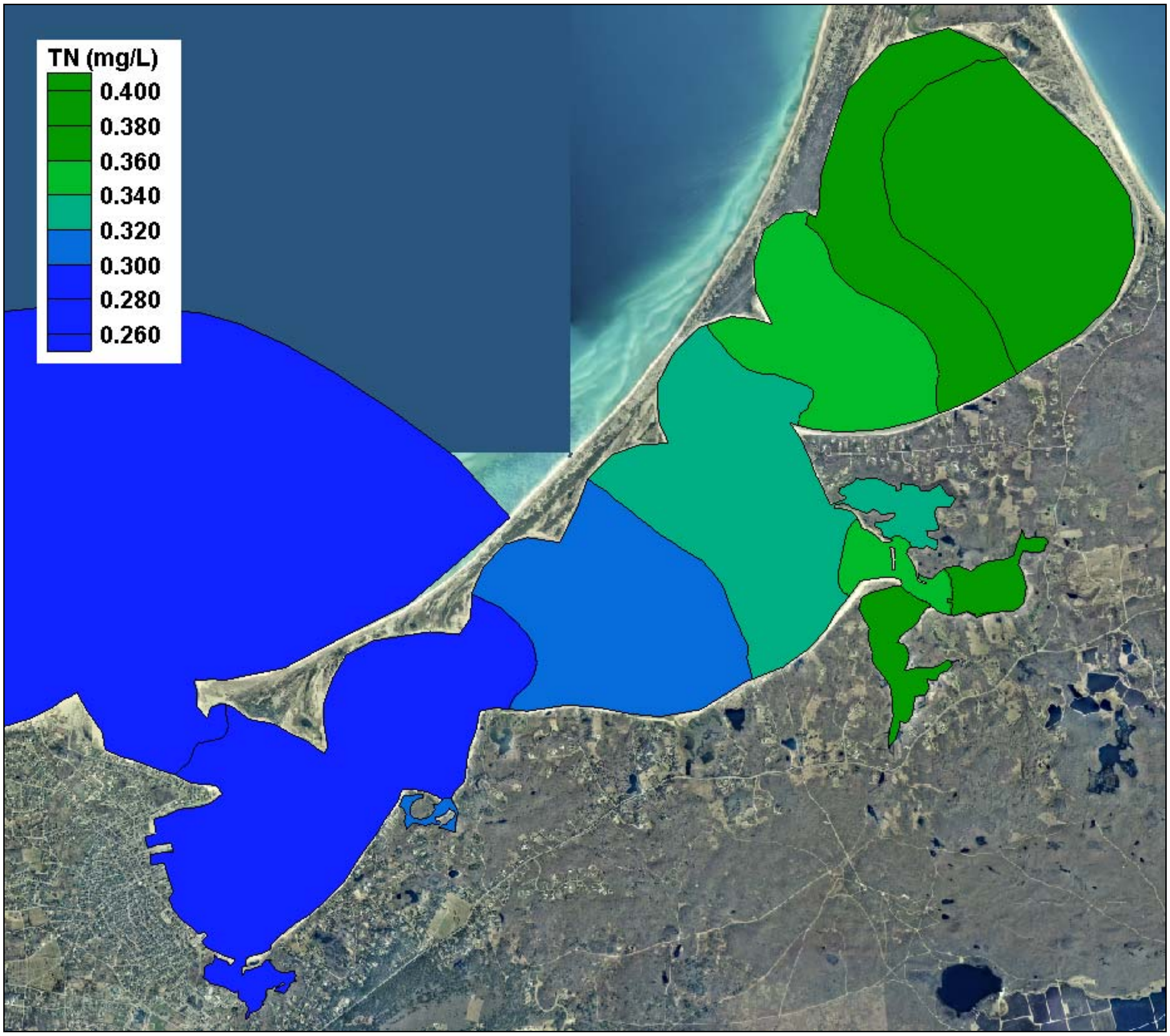


Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Nantucket Harbor system.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

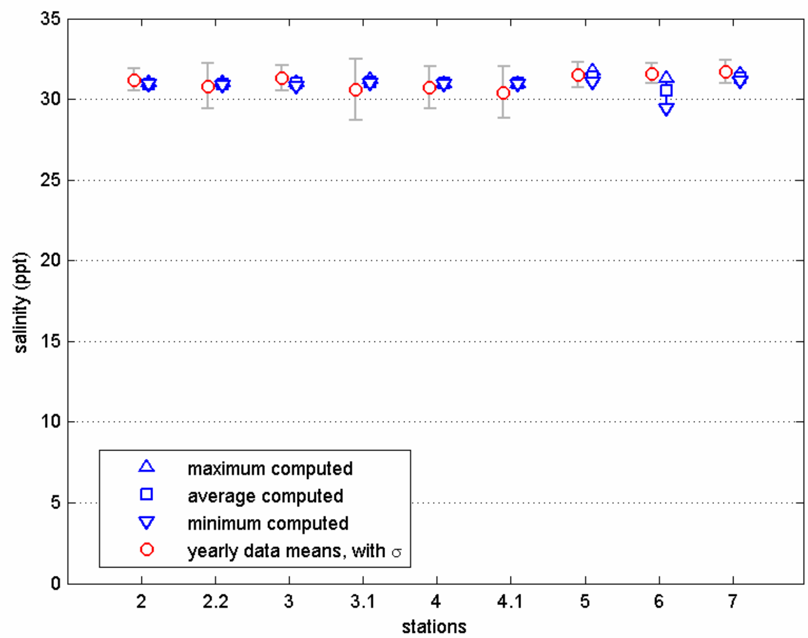


Figure VI-5. Comparison of measured and calibrated model output at stations in Nantucket Harbor. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset.

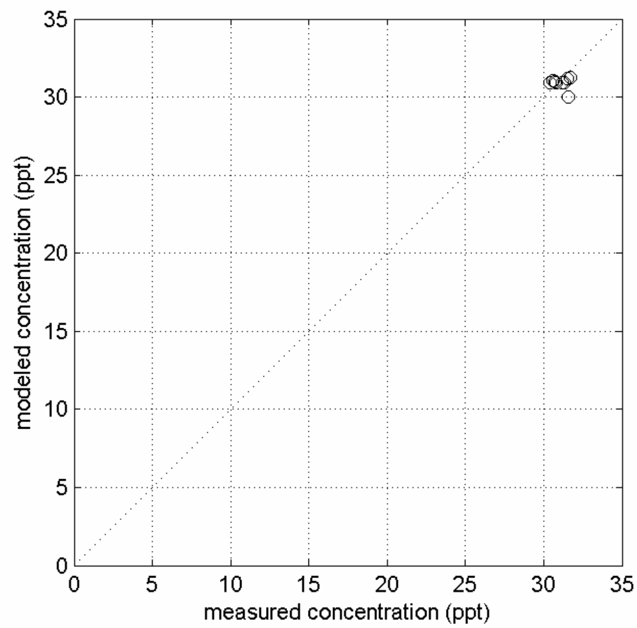


Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. RMS error for this model verification run is 0.65 ppt or 2.03% of measurements.

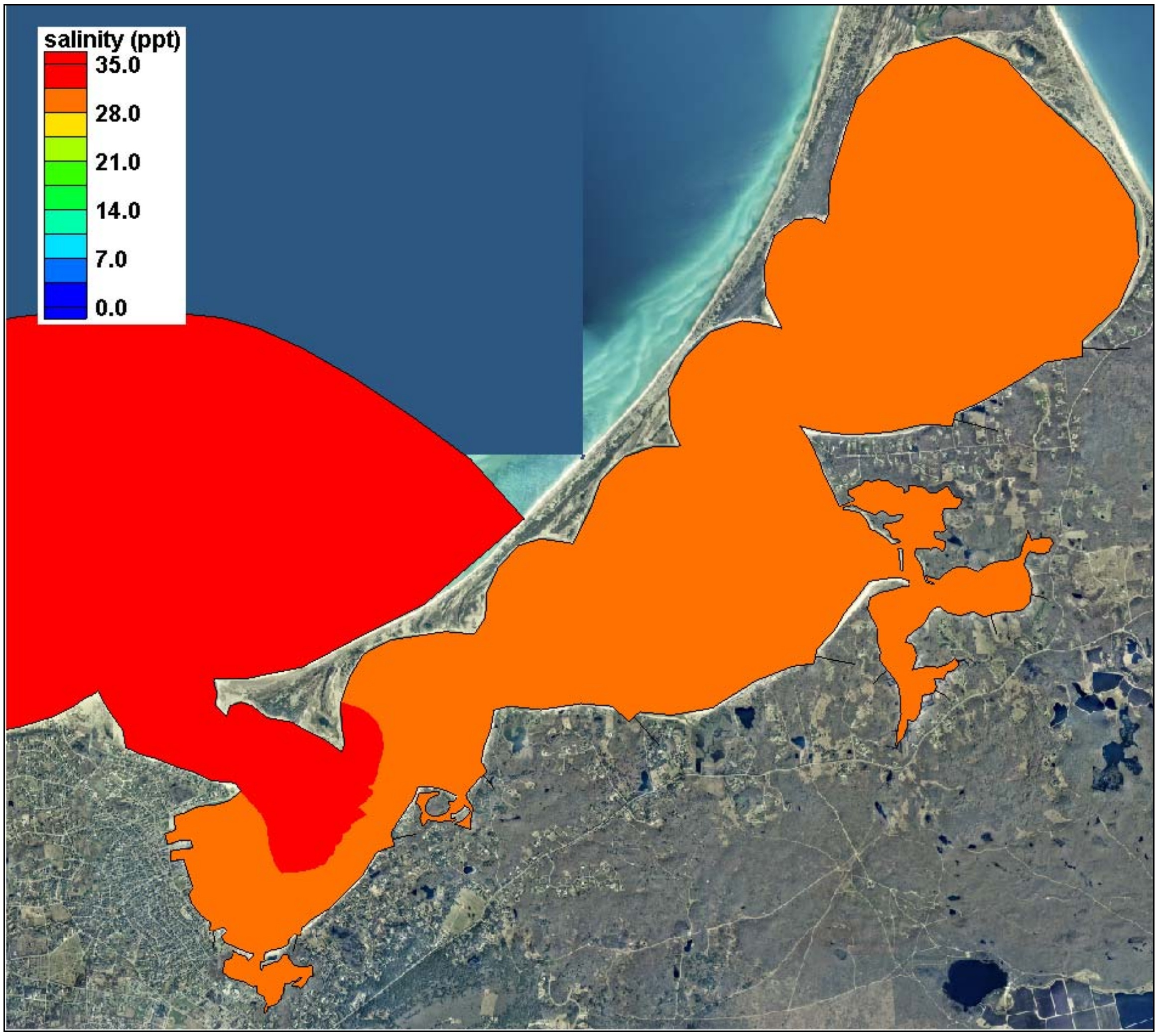


Figure VI-7. Contour Plot of modeled salinity (ppt) in the Nantucket Harbor system.

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out (scenarios "A" and "B"), and no-anthropogenic ("no-load") loading scenarios of the Nantucket Harbor system. 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 "A" (kg/day)	build-out "A" % change	build out "B" (kg/day)	build-out "B" % change	no load (kg/day)	no load % change
Head of the Harbor	1.858	2.375	+27.9%	2.375	+27.9%	0.526	-71.7%
Polpis Harbor	3.529	3.868	+9.6%	3.868	+9.6%	1.836	-48.0%
Quaise Basin	2.123	2.422	+14.1%	2.422	+14.1%	0.896	-57.8%
Town Basin	15.901	20.118	+26.5%	16.438	+3.4%	1.321	-91.7%
System Total	23.411	28.784	+22.9%	25.104	+7.2%	4.578	-80.4%

VI.2.6.1 Build-Out

Two build-out scenarios were modeled for the Nantucket Harbor system. For build-out scenario "A", wastewater loads from all developable properties with the Town sewer district were treated as septic groundwater inputs to the Town basin. For scenario "B", all remaining developable properties were assumed to be connected to the town sewer system and therefore not contribute to the groundwater load to the Harbor.

A breakdown of the total nitrogen load entering each sub-embayment is shown in Tables VI-5 and VI-6 for the two modeled build-out scenarios. The benthic flux for the build-out scenarios is assumed to vary proportional to the watershed load, where an increase in watershed load will result in an increase in benthic flux (i.e., a positive change in the absolute value of the flux), and *vise versa*.

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Table VI-5. **Build-out scenario "A"** sub-embayment and surface water loads used for total nitrogen modeling of the Nantucket Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Head of the Harbor	2.375	22.239	-17.677
Polpis Harbor	4.093	2.190	28.120
Quaise Basin	2.405	20.126	44.654
Town Basin	20.090	13.888	-2.659
System Total	28.964	58.443	52.439

Table VI-6. **Build-out scenario "B"** sub-embayment and surface water loads used for total nitrogen modeling of the Nantucket Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Head of the Harbor	2.375	22.239	-17.598
Polpis Harbor	4.093	2.190	27.709
Quaise Basin	2.405	20.126	44.274
Town Basin	16.411	13.888	-2.642
System Total	25.285	58.443	51.744

Following development of the nitrogen loading estimates for the build-out scenarios, the water quality models of each system were run to determine nitrogen concentrations within each sub-embayment (Table VI-7 and VI-8). Total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios. Results from both build-out scenarios are presented in Tables VI-7 and VI-8. For both cases the increase in modeled TN concentrations is less than 1% at all monitoring stations, with the largest increases occurring at the monitoring stations in Polpis Harbor Contour plots showing TN concentrations throughout the Harbor are presented in Figures VI-8 and VI-9, for both build-out scenarios.

Table VI-7. Comparison of model average total N concentrations from present loading and the **build-out scenario "A"**, with percent change, for the Nantucket Harbor system. The sentinel threshold station is in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out "A" (mg/L)	% change
Head of the Harbor - Upper	2	0.397	0.400	+0.7%
Head of the Harbor - Mid	2.2	0.390	0.392	+0.7%
Head of the Harbor - Lower	**2.1**	**0.353**	**0.355**	**+0.6%**
Pocomo Head	3	0.340	0.342	+0.6%
Quaise Basin	3.1	0.325	0.327	+0.5%
East Polpis Harbor	**4**	**0.361**	**0.364**	**+0.9%**
West Polpis Harbor	4.1	0.371	0.374	+0.9%
Abrams Point	5	0.296	0.297	+0.3%
Monomoy	6	0.291	0.292	+0.5%
Mooring Area	7	0.285	0.286	+0.3%

Table VI-8. Comparison of model average total N concentrations from present loading and the **build-out scenario "B"**, with percent change, for the Nantucket Harbor system. The sentinel threshold station is in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out "B" (mg/L)	% change
Head of the Harbor - Upper	2	0.397	0.398	+0.3%
Head of the Harbor - Mid	2.2	0.390	0.391	+0.3%
Head of the Harbor - Lower	**2.1**	**0.353**	**0.354**	**+0.3%**
Pocomo Head	3	0.340	0.340	+0.2%
Quaise Basin	3.1	0.325	0.326	+0.2%
East Polpis Harbor	**4**	**0.361**	**0.363**	**+0.5%**
West Polpis Harbor	4.1	0.371	0.373	+0.5%
Abrams Point	5	0.296	0.296	+0.1%
Monomoy	6	0.291	0.291	+0.1%
Mooring Area	7	0.285	0.285	+0.1%

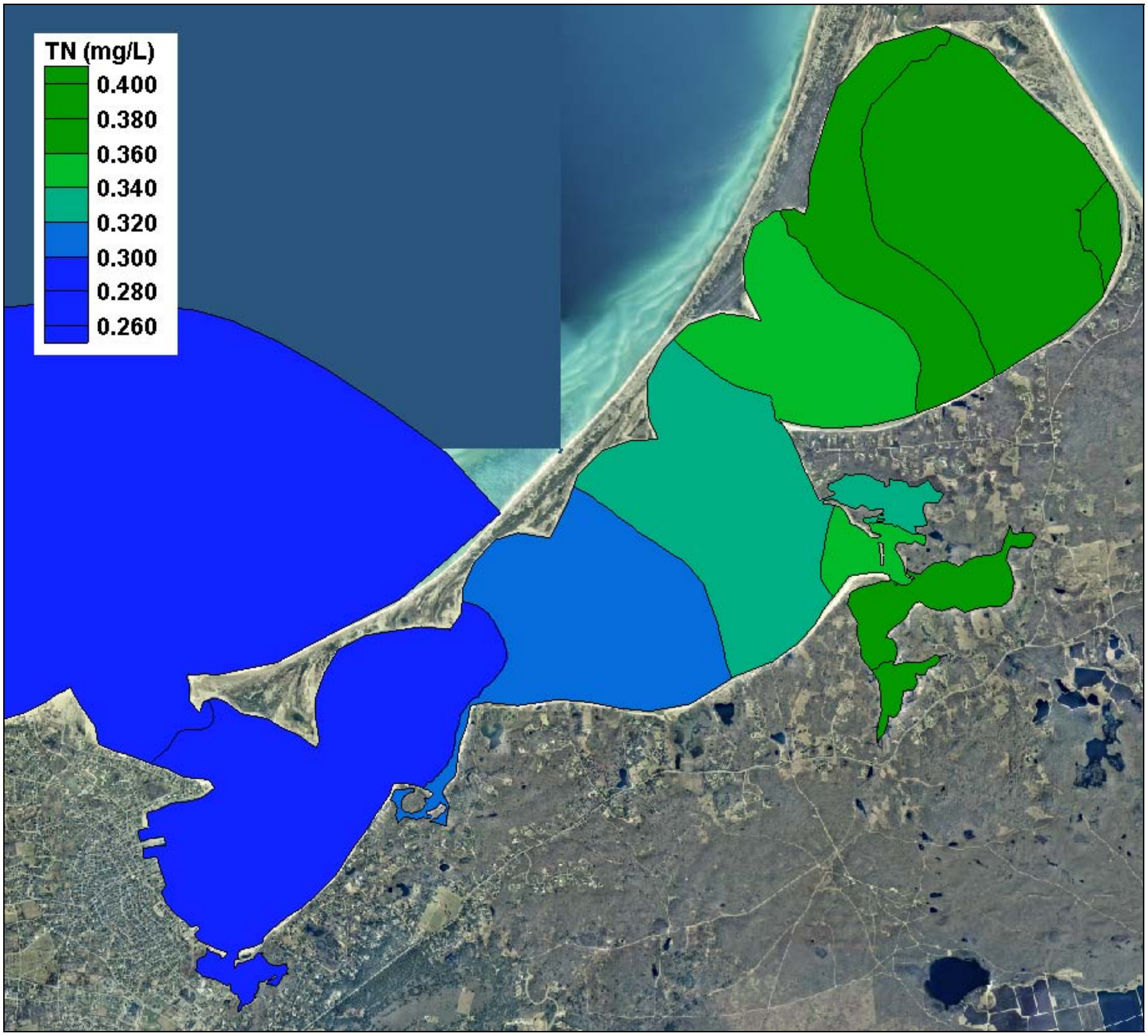


Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Nantucket Harbor system, for projected build-out scenario "A" loading conditions.

VI.2.6.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering each sub-embayment for the no anthropogenic load ("no load") scenarios is shown in Table VI-9. The benthic flux input to each embayment was reduced (toward zero) based on the reduction in the watershed load (as discussed in §VI.2.6.1). Compared to the modeled present conditions and build-out scenario, atmospheric deposition directly to each sub-embayment becomes a greater percentage of the total nitrogen load as the watershed load and related benthic flux decrease.

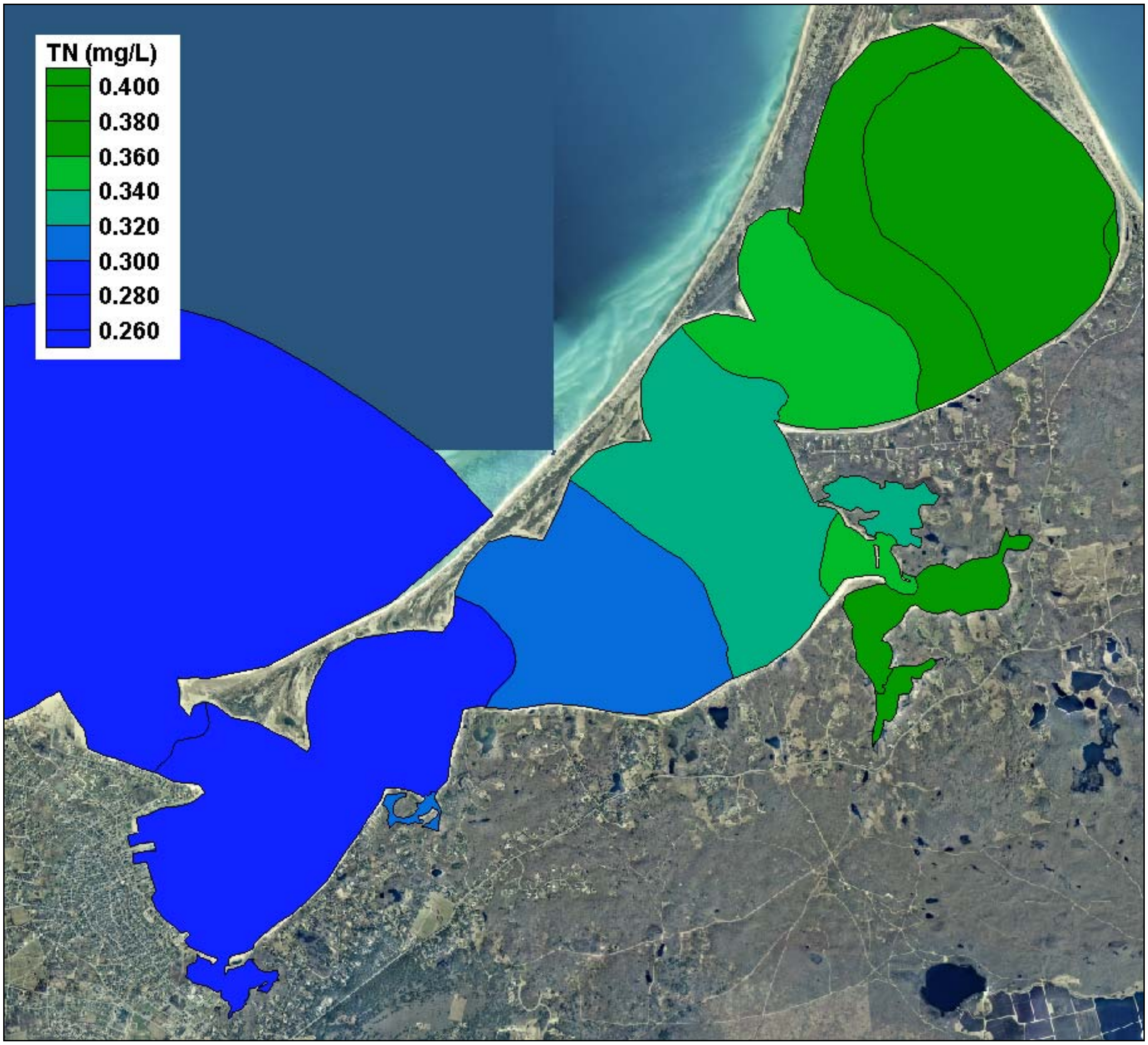


Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in the Nantucket Harbor system, for projected build-out scenario "B" loading conditions.

Table VI-9. "**No anthropogenic loading**" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Nantucket Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Head of the Harbor	0.526	22.239	-16.405
Polpis Harbor	1.836	2.190	25.226
Quaise Basin	0.896	20.126	41.619
Town Basin	1.321	13.888	-2.975
System Total	4.578	58.443	47.466

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations at each monitoring station. Again, total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was small as shown in Table VI-10, with reductions less than 3% occurring at all stations in the Harbor system. A contour plot showing TN concentrations throughout the system is shown pictorially in Figure VI-10.

Table VI-10. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the Nantucket Harbor system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The sentinel threshold station is in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	no load (mg/L)	% change
Head of the Harbor - Upper	2	0.397	0.387	-2.5%
Head of the Harbor - Mid	2.2	0.390	0.380	-2.5%
Head of the Harbor - Lower	**2.1**	**0.353**	**0.345**	**-2.1%**
Pocomo Head	3	0.340	0.333	-2.0%
Quaise Basin	3.1	0.325	0.319	-1.8%
East Polpis Harbor	**4**	**0.361**	**0.351**	**-2.8%**
West Polpis Harbor	4.1	0.371	0.360	-2.9%
Abrams Point	5	0.296	0.293	-1.1%
Monomoy	6	0.291	0.286	-1.8%
Mooring Area	7	0.285	0.282	-1.0%

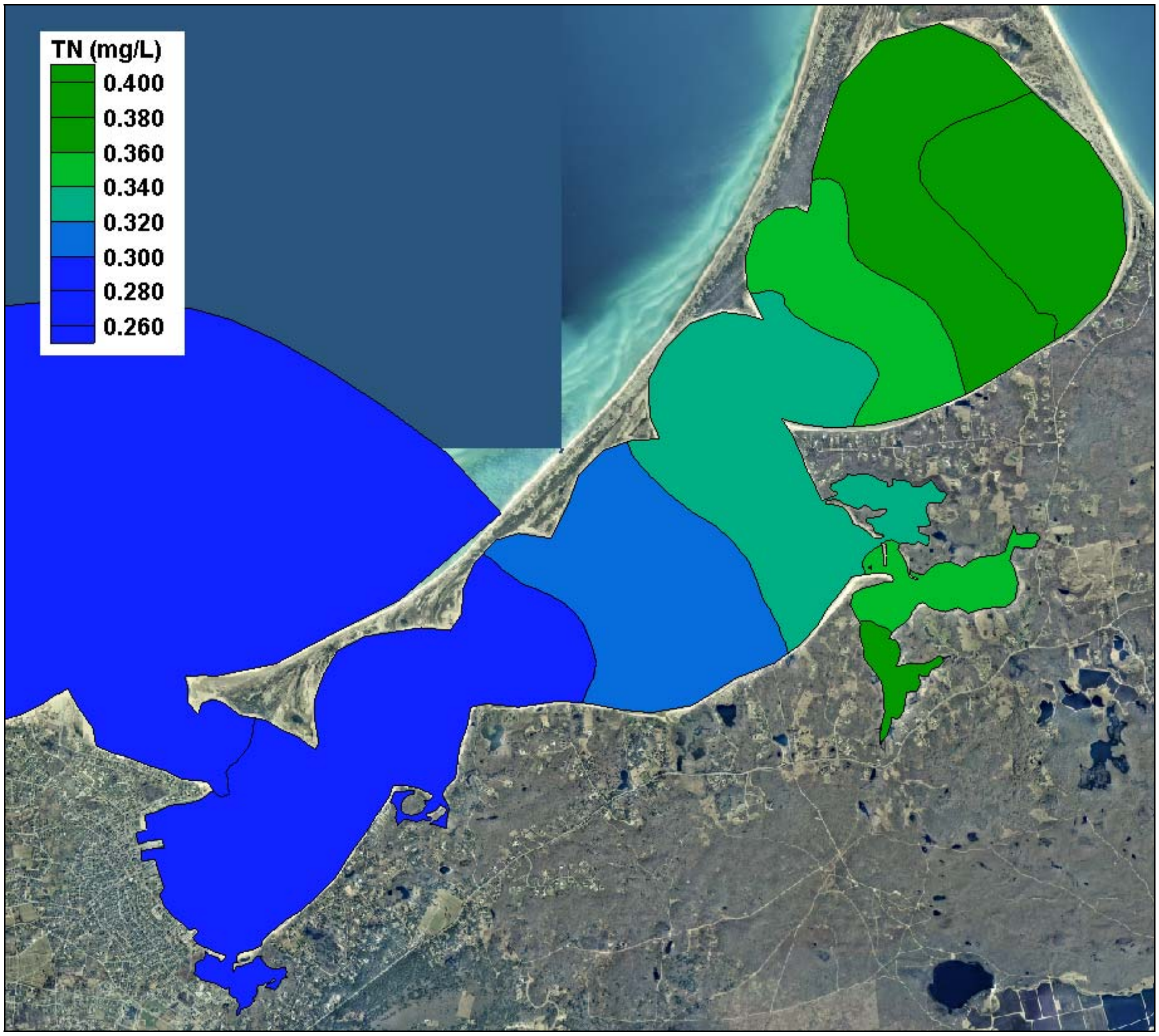


Figure VI-10. Contour plot of modeled total nitrogen concentrations (mg/L) in Nantucket Harbor, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Nantucket Harbor embayment system in the Town of Nantucket, Nantucket Island, MA, our assessment is based upon data from the water quality monitoring database developed by the Town of Nantucket and surveys of eelgrass distribution from the MassDEP mapping program (1951, 1995, 2001) with information from the Town of Nantucket Health Department studies (1982, 1989), Harbor-wide surveys of macro-algal distribution undertaken by the Nantucket Harbor Study, benthic animal communities (Summer 1992, Spring 1994, Fall 2003), sediment characteristics, and dissolved oxygen records obtained during the summer of 1992 coupled with grab sample data from 1988-2005. 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 these systems (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen thresholds determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll a (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed dissolved oxygen sensors within the Nantucket Harbor system (inclusive of Polpis Harbor) to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Nantucket Harbor system was conducted for comparison to historic records (MassDEP Eelgrass Mapping Program, C. Costello). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the Nantucket Harbor system, temporal changes in eelgrass distribution provides a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing) in nutrient enrichment.

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

VII.2 BOTTOM WATER DISSOLVED OXYGEN

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

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Nantucket Harbor system (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the Nantucket Harbor System was collected during the summer of 1992. The results of the mooring analysis were compared to the results from grab samples from the various water quality monitoring programs, 1988-2005.

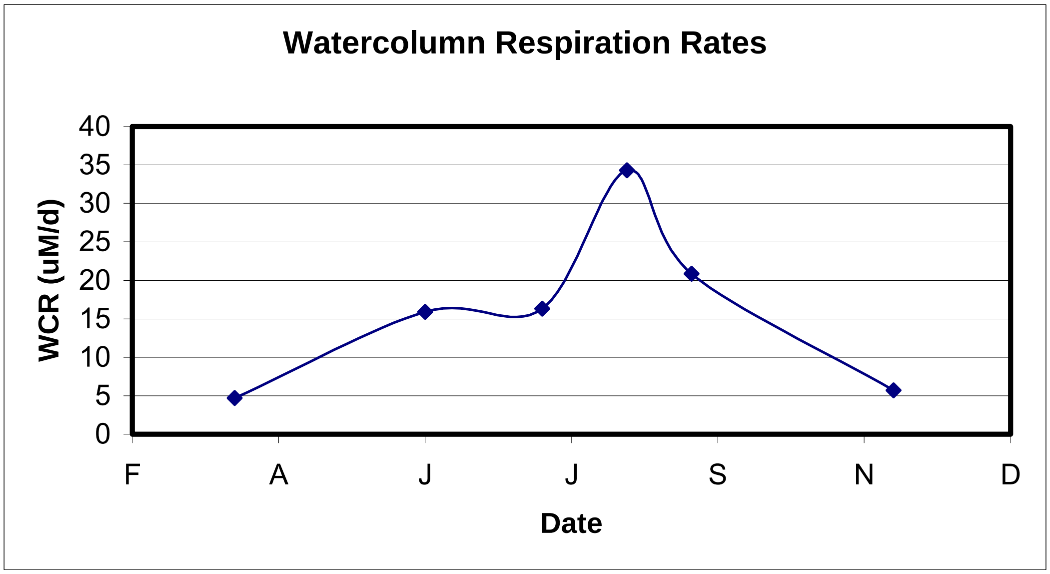


Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Nantucket Harbor system evaluated in this assessment showed high frequency variation, apparently related to diurnal and sometimes tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. Nantucket Harbor bottom waters tended to have less diurnal variation than most other embayments in southeastern Massachusetts, likely due to its relatively low level of nitrogen enrichment. However, even in this system, the temporal variation in bottom water dissolved oxygen concentration observed at each mooring site, supports the value of continuous monitoring within this system.

Dissolved oxygen records were examined both for temporal trends and to determine the percent of the 35-42 day deployment period that dissolved oxygen was below/above various benchmark concentrations (Table VII-1). The data indicates 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. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions. The level of oxygen depletion and the magnitude of daily oxygen excursion indicates moderately nutrient enriched waters and impaired habitat quality at one (Pocomo) out of four mooring sites within the Harbor system (Figures VII-4 through VII-7). The oxygen data is consistent with a moderate level of organic matter loading from phytoplankton production indicative of slight nitrogen enrichment. 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). While daily oxygen excursions occurred, generally day time levels did not exceed atmospheric equilibration, indicating moderate enrichment.

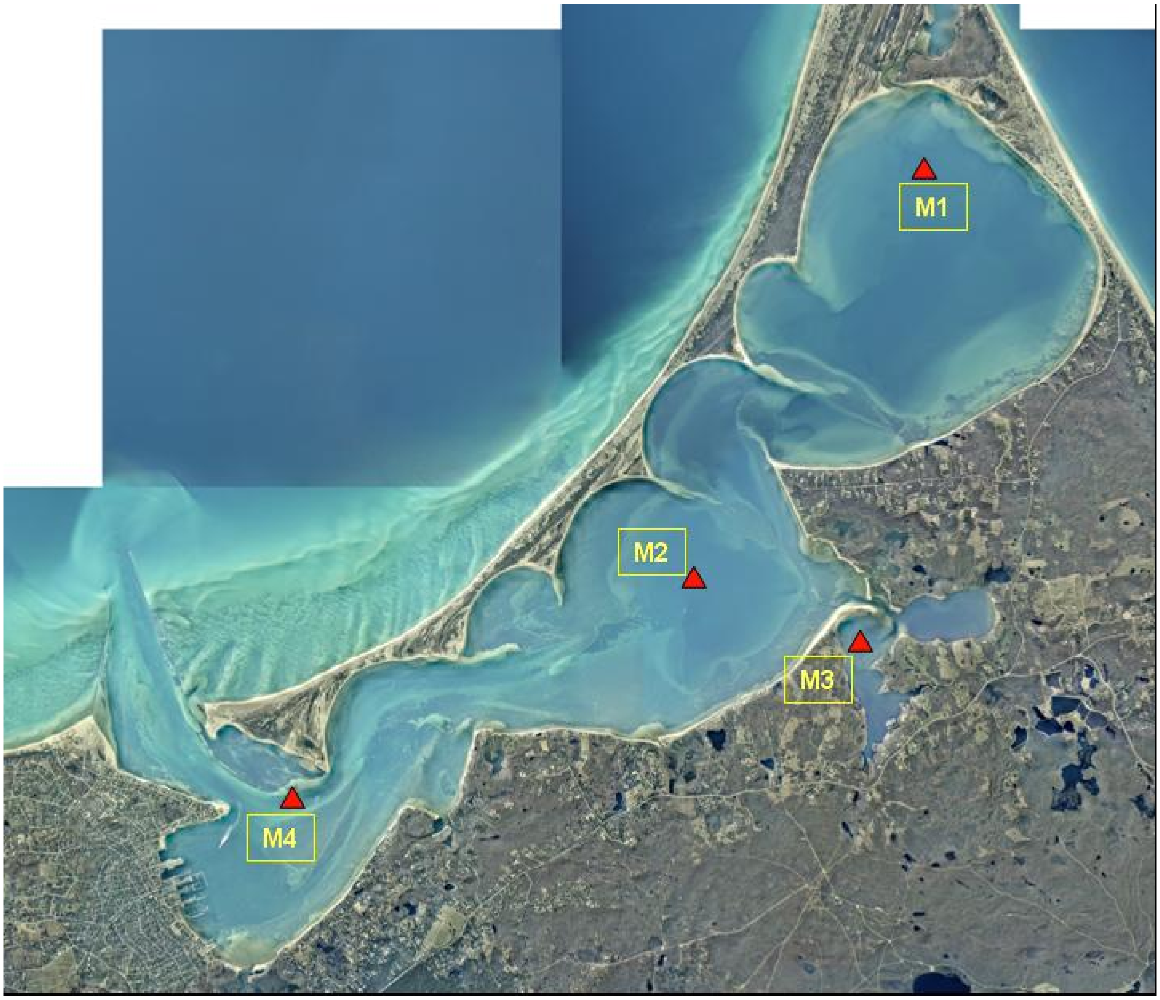


Figure VII-2. Aerial Photograph of the Nantucket Harbor system on the island of Nantucket showing locations of Dissolved Oxygen mooring deployments within each of the main basins, conducted by the Nantucket Harbor Study (1997).

Based upon the findings of higher nutrient and organic matter levels within the upper versus lower Harbor (see Chapter VI), which result from the flushing gradient and nutrient inputs from the watershed and regeneration from sediments, an analysis of the oxygen balance of the component Harbor regions was conducted. It is through bottom water oxygen depletion that organic matter accumulations resulting from nutrient loadings impact animal communities. The infaunal survey suggested that periodic low oxygen conditions were the likely ecological stressor controlling the ecological health of the low and moderate habitat quality areas of the upper Harbor.

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

	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)
Pocomo, Nantucket	6/24/1992	8/5/1992	42.2	12.09	5.72	0.26	0.00
			Mean	0.36	0.38	0.09	NA
			Min	0.01	0.06	0.04	0.00
			Max	4.82	0.86	0.13	0.00
			S.D.	0.89	0.27	0.04	NA
Harbor Channel, Nantucket	6/24/1992	8/5/1992	42.1	0.45	0.04	0.00	0.00
			Mean	0.07	0.04	NA	NA
			Min	0.01	0.04	0.00	0.00
			Max	0.17	0.04	0.00	0.00
			S.D.	0.07	NA	NA	NA
Polpis, Nantucket	6/24/1992	8/6/1992	42.3	0.00	0.00	0.00	0.00
			Mean	0.00	0.00	0.00	0.00
			Min	0.00	0.00	0.00	0.00
			Max	0.00	0.00	0.00	0.00
			S.D.	NA	NA	NA	NA
Wauwinwet, Nantucket	6/23/1992	7/29/1992	35.7	1.96	0.13	0.00	0.00
			Mean	0.20	0.13	N/A	N/A
			Min	0.06	0.13	0.00	0.00
			Max	0.37	0.13	0.00	0.00
			S.D.	0.13	N/A	N/A	N/A

Low oxygen levels are a common result of elevated nutrient inputs to coastal embayments. While the nutrient enhancement of phytoplankton (or macro-algal) production can directly impact habitat quality, for instance by shading out eelgrass beds, the direct stress on communities typically results from oxygen depletion. Therefore, while nutrient loading is the ultimate factor, bottom water oxygen concentration is the proximate factor which determines nutrient related habitat quality. The level of nutrient/organic matter loading which a system can safely assimilate is determined by the resulting rate of oxygen uptake during the organic matter decay and the rate of oxygen resupply. Within Nantucket Harbor the rate of oxygen uptake is primarily the result of degradation of organic matter produced within the Harbor versus resupply from the atmosphere via mixing. The observation of periodic restrictions in vertical mixing within the upper basins due to stratification supports the potential for periodic oxygen depletions in these regions.

Since oxygen levels are controlled by the balance between consumption and resupply, oxygen concentrations can change rapidly in coastal waters. This is especially true in eutrophic embayments where shifts of >6mg L^{-1} can occur diurnally (Taylor and Howes 1994). The level of stress to benthic communities of low oxygen conditions (hypoxia) is determined by both the frequency and duration of hypoxia. Periodic depletions of bottom water oxygen of relatively short duration can be sufficient to re-structure communities.

Given the rapid fluctuations of oxygen levels and that only periodic short duration oxygen depletion of bottom waters is generally necessary to produce infaunal shifts similar to those in upper Nantucket Harbor, we deployed continuously recording oxygen sensors within the Harbor (Figure VII-2). Since stratification and oxygen uptake are greatest within the summer months, sampling focused upon this interval of maximum likelihood for the occurrence of low bottom-water dissolved oxygen. Measurements of bottom water oxygen levels were supported by determination of rates of oxygen uptake by sediments and water column. The directly measured rates of system oxygen consumption allow the prediction of sensitivity of each basin to periodic oxygen depletions, as well as an indication of the impact on oxygen levels of increased nitrogen input.

Oxygen balances for the upper and lower Harbor indicated that the rates of oxygen uptake within the sediments and bottom waters during the warmer summer months were sufficient to discernibly lower the oxygen pool during a 24 hour stratification event (Figure VII-3). Within Polpis Harbor and Head of Harbor, uptake was sufficient to remove half of the oxygen from the bottom 1 meter of watercolumn within 1 day. Given horizontal and vertical mixing, it is unlikely that only the bottom 1 meter would contribute oxygen to support this uptake. However, this analysis does indicate the potential for oxygen stress to benthic communities in the deeper waters of Head of the Harbor and Polpis Harbor. In contrast, the lower Harbor would require more than twice the non-mixed interval (>48 hours) to achieve the same level of depletion (Figure VII-3). Given the flushing and stratification characteristics of the Harbor regions and the rates of oxygen consumption, some level of oxygen depletion is likely within the upper but not lower Harbor basins. The only reliable method for reducing the rate of sediment oxygen uptake and nutrient release from the upper basins is to decrease the rate of organic matter deposition by decreasing rate of production through reduced nitrogen inputs from the watershed or increasing the rate of export of organic matter to the Sound through increased rates of water exchange.

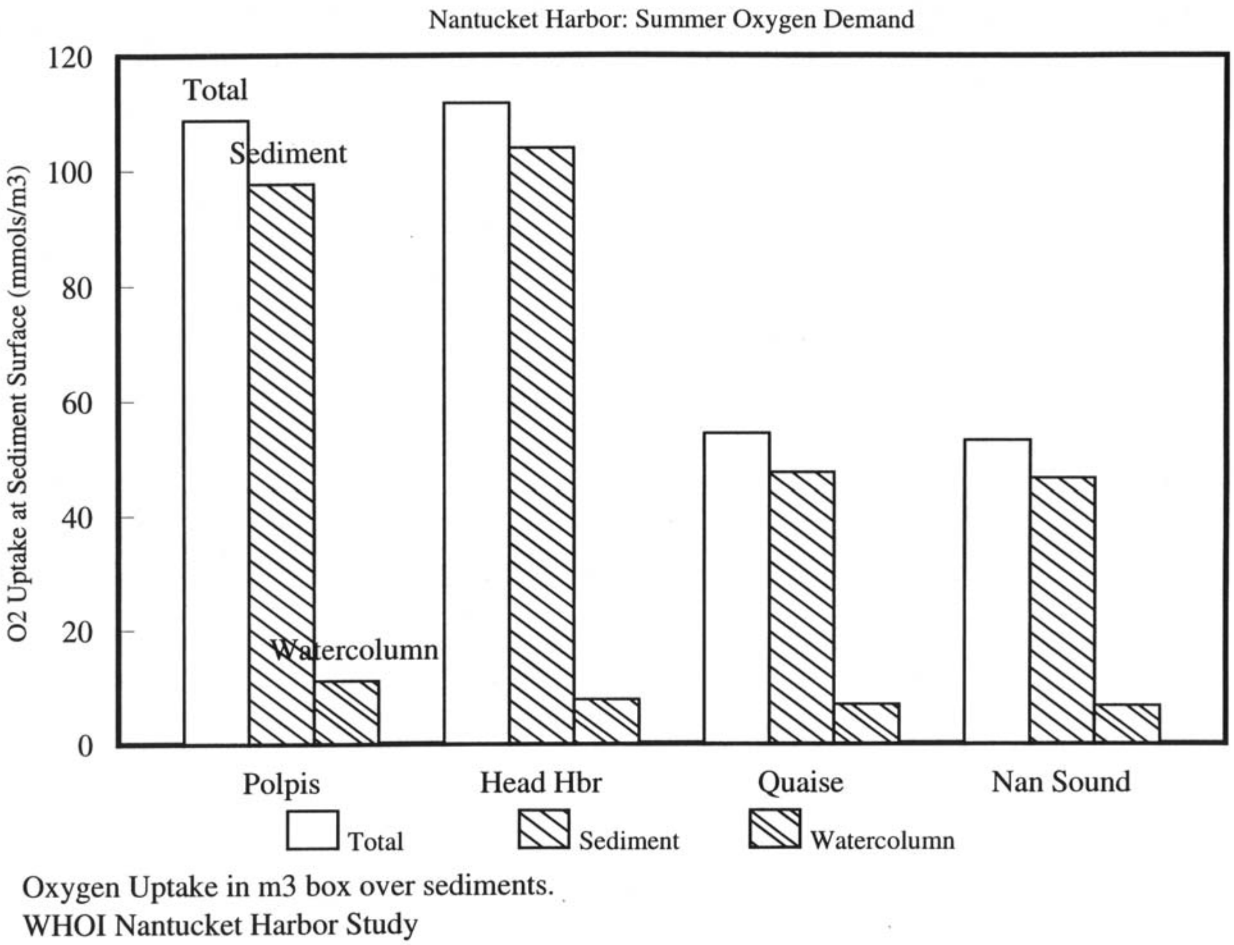


Figure VII-3. Rate of oxygen consumption (mmol m^2 d^{-1}) within the bottom sediments and overlaying 1 meter of water. These data indicate that Head of the Harbor and Polpis Harbor are the most susceptible to oxygen depletion resulting from a brief period of water column stratification. At these rates of consumption, only 24 hours would be required to remove half the oxygen in a stratified water column that is initially at full oxygen saturation thus creating a stressful environment for infuana.

The continuously recording oxygen sensor arrays were placed on moorings at 4 locations along the organic matter/nutrient gradient with the Harbor (Figure VII-2). Within the basins in Head of Harbor and Quaise the sensor was placed within the basin, but not in the deepest region. The goal was to determine if the observed assessment of habitat quality was the result periodic low oxygen conditions as discussed in the above sections. Observation of low oxygen conditions is generally accepted to be indicative of a system beyond its assimilative capacity for nutrients, but does not reflect the role of natural versus anthropogenic causes.

Within the highly flushed and generally well mixed waters the lower Harbor (M4, Figure VII-7), bottom waters were well oxygenated (>6mg L^{-1}, 188 uM = 6 mg L^{-1}). Both tidal and diurnal fluctuations were observed in the oxygen pool. The excursions below 6 mg L^{-1} were isolated events, rather than a prolonged depletion such as generally associated with a phytoplankton bloom. However, these variations were small and overall the oxygen conditions are consistent with the observations of healthy infaunal and eelgrass communities (see Sections VII.3, VII.4 below). While Polpis Harbor also exhibited well oxygenated conditions, larger diurnal variations were recorded (Figure VII-4). The higher diurnal fluctuations indicate waters supporting higher phytoplankton biomass. The fluctuations result from the large production of oxygen during photosynthesis and the high rates of dark period respiration. The effect is "excess" oxygen levels during day light and "under-saturated" levels at night. The lack of a low oxygen event is likely the result of the lack of watercolumn stratification within this shallow system. The cause of the loss of eelgrass within Polpis Harbor (see below) may be still be due to infrequent low oxygen events or the turbidity of its waters (low light penetration) resulting from phytoplankton production and the input of freshwaters. In addition, the high organic matter deposition resulting in enhanced levels of sediment oxygen uptake and reducing sediments likely inhibits recolonization of much of this system. The role of epiphytes in this nutrient enriched embayment cannot be assessed at this time.

Quaise basin (M2, Figure VII-2, Figure VII-5) showed both significant diurnal oxygen fluctuations and an overall oxygen decline, although not to levels of high stress. There was a single "event" of a few days when nighttime oxygen levels reached 4 mg/L, but returned to ~5 mg L^{-1} the following day. Since the meter was located deeper within the basin, oxygen levels throughout most of the basin area were almost certainly higher given their shallower depths, only in the "deep hole" was oxygen depletion likely greater. Assessing oxygen conditions within the Quaise basin indicates generally non-stressful oxygen levels, except for the deep basin. However, it is likely that the presence of the deep hole (~30') creates a geomorphological (natural) cause of the low dissolved oxygen, as it creates a depositional area and is susceptible to periodic watercolumn stratification. The depositional nature of the basin was observed by field dive staff, who observed large accumulations of eelgrass detritus in the late fall and early spring. It is likely that a major function of these periodically deposited mats is to smother the infaunal communities at the bottom of the "hole", as the surficial sediments beneath them were observed to lack a surface oxygenated layer with hydrogen sulfide reaching the sediment/water interface. There is evidence that the mats are transitory and do not occur each year. Their deposition is likely mediated by water circulation which is both tidally and storm driven in this system.

Similarly, Head of the Harbor showed generally high oxygen levels (Figure VII-6). As at Quaise, the meter was deeper in the basin and observed oxygen depletions were greater than experienced by bottomwaters throughout most of the basin area. The oxygen conditions are consistent with the observed distribution of habitat quality throughout the Harbor System, with the deep waters showing oxygen depletion, but with oxygen levels generally supportive of a high habitat quality for infauna. However, since the system does show oxygen levels less than full atmospheric saturation, additional organic matter loads, (e.g. through nitrogen inputs) will likely increase the magnitude and frequency of the oxygen declines.

The oxygen records from the moored instrumentation are consistent with the results from the periodic grab samples by the water quality monitoring programs. While grab samples are not necessarily a good indication of the degree of oxygen depletion in embayment waters, given the potential temporal variation, the data can be used if there are sufficient numbers of sampling dates. Given the 81 sampling dates in Nantucket Harbor from 1988-2005, an analysis was conducted by the MEP Technical Team. This analysis confirms the results of the mooring data. At all stations and dates throughout the Nantucket Harbor System, only a single sample was found to be <4 mg L^{-1} and that was from the deep water in the Head of the Harbor basin (7 m, 3.68 mg L^{-1}) in 1993. The next lowest value recorded in the System was 4.4 mg L^{-1}. In Quaise and the Town basin there were only 5 and 8 samples <6 mg L^{-1}, with only 1 sample < 5 mg L-1 (4.81 mg L^{-1}). Polpis Harbor showed slightly more frequent, but still only moderate depletions, with the East and West basins having 4 and 3 dates between 4.4-5.99 mg L-1 and a total of 12 dates <6 mg L^{-1}. These data support the contention that except in the deep holes of the main Harbor, oxygen depletion is generally only short term and moderate, with the overall summer conditions showing oxygen levels supportive of healthy to moderately healthy infaunal habitat.

Overall, oxygen within the Harbor bottom waters appears to remain at ecologically healthy levels, except for periodic oxygen depletion within the deepest portions of the Quaise and Wauwinet basins. However, as there were some oxygen depletions below 5 mg L-1 in the main basins (although infrequent), it appears that the system is at or just beyond it ability to assimilate additional nitrogen/organic matter. Increasing organic matter deposition either through direct inputs or via enhanced production from increased nutrient loading is nearly certain to increase the level of oxygen related ecological stress. Decreasing organic matter deposition, either through lowered production or increased export should result in improvements in benthic habitat within these basins. However, other factors such as deposition of macrophyte debris and light penetration may also play a role in habitat quality in some areas.

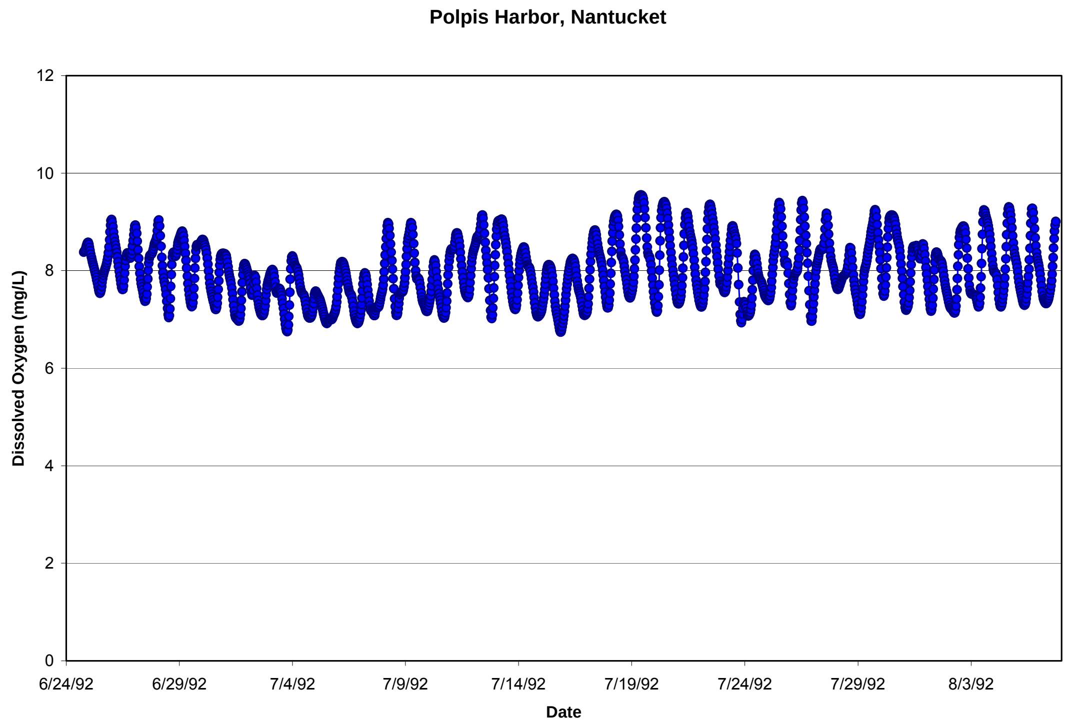


Figure VII-4. Bottom water record of dissolved oxygen at the Polpis Harbor station, Summer 1992.

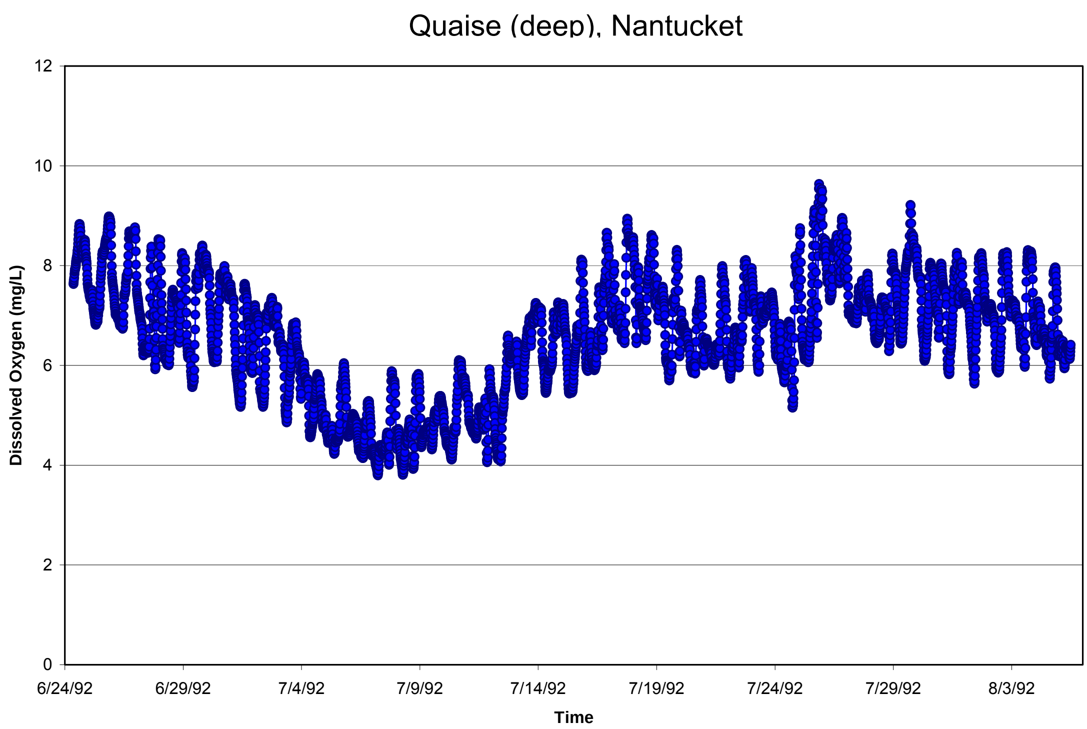


Figure VII-5. Bottom water record of dissolved oxygen in the deeper waters of the Quaise Basin (Pocomo Mooring - M2), Summer 1992.

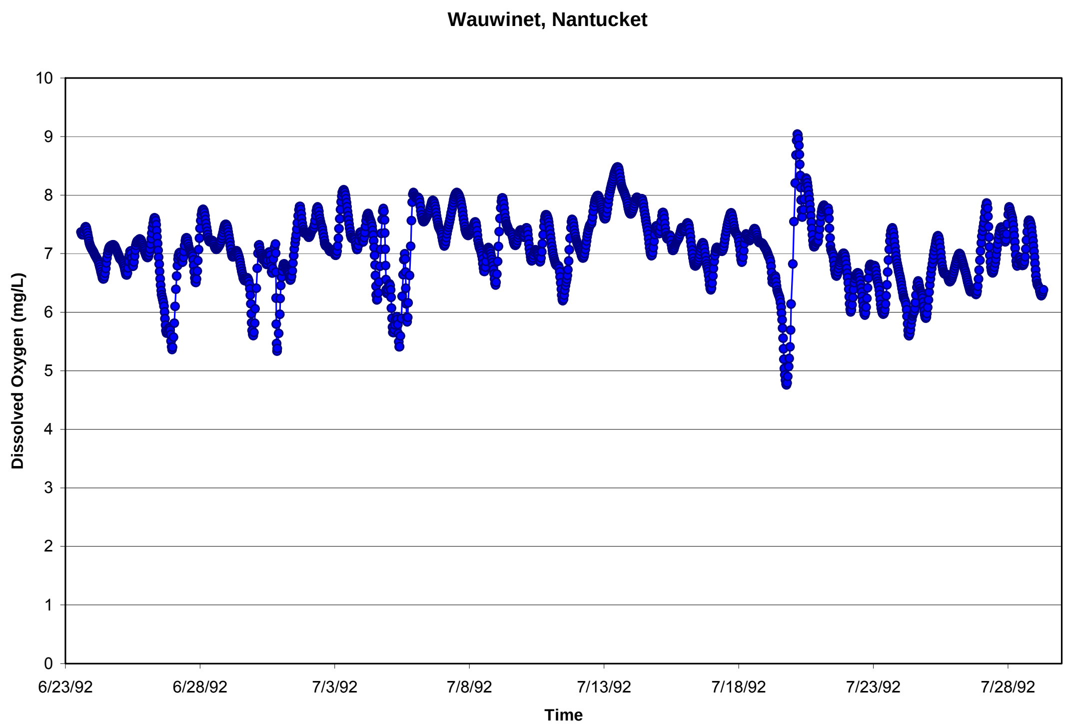


Figure VII-6. Bottom water record of Dissolved Oxygen at the Head of the Harbor (Wauwinet) station, Summer 1992.

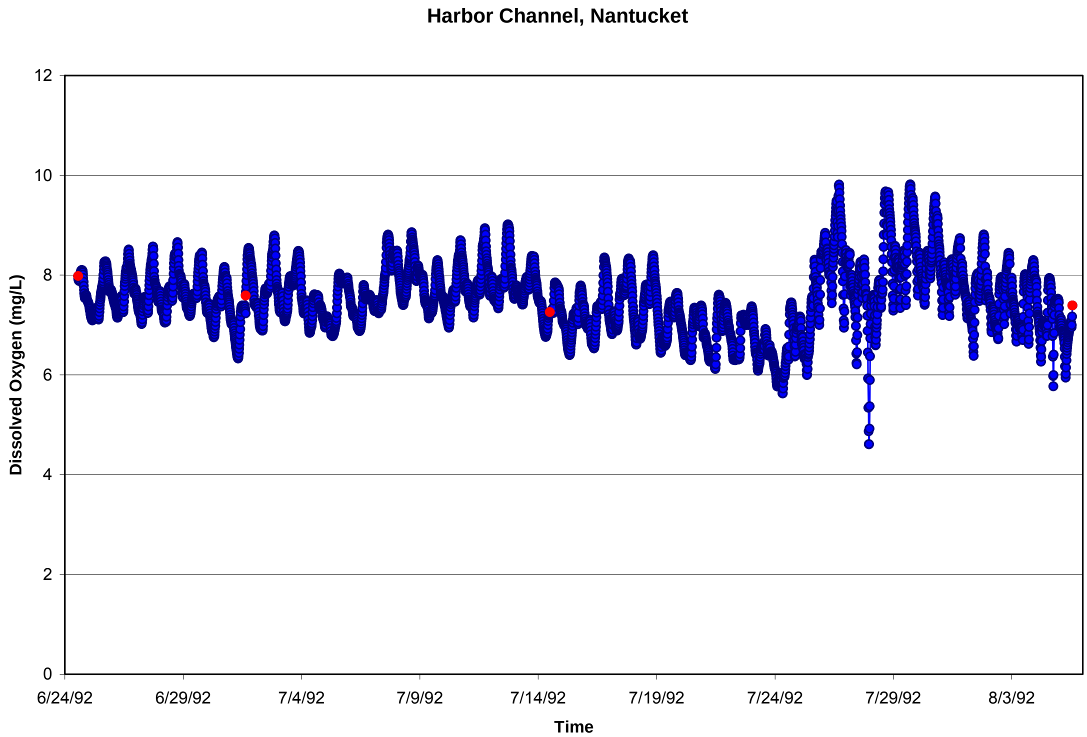


Figure VII-7. Bottom water record of Dissolved Oxygen at the Harbor Channel station, Summer 1992. Calibration samples represented as red dots.

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Complementing the eelgrass surveying work initially conducted by C. Costello (DEP Eelgrass Mapping Program) on Nantucket Harbor for the 1997 Nantucket Harbor Water Quality Study, additional eelgrass survey work and analysis of historical data was conducted for the Nantucket Harbor system. This additional mapping effort was also conducted by the MassDEP Eelgrass Mapping Program as part of the MEP Technical Team. Surveys were conducted in 1995 (original Nantucket Harbor study dated 1997) and 2001, as part of this program. Additional analysis of available aerial photos from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. The 1951 data were only anecdotally validated, while the 1995 and 2001 maps were field validated. However, field validated surveys were also collected in 1982 and 1989 (Kelley 1982, 1989) providing important additional information for the MEP Technical Team's assessment. The field validated 1989 survey was used with the 1951 MassDEP analysis as an important benchmark for evaluating temporal changes in eelgrass bed distribution over the past several decades.

Eelgrass beds are essential for scallop production and also play a critical role in the stability of Harbor sediments. Loss of eelgrass beds is frequently associated with excessive nutrient loading to an embayment. Since eelgrass is a rooted plant it requires that light penetrate to the bottom for growth. In areas where increased nutrient inputs stimulate phytoplankton growth within the overlying water, light transmission declines and eelgrass can be lost. In addition, increased nutrients stimulate the growth of organisms on the eelgrass leaves (epiphytes) and may also result in low oxygen conditions from the decay of the increased organic matter production in bottom sediments. As with shading, both the growth of epiphytes and periodic low oxygen conditions stress the plants and can cause the loss of eelgrass beds.

The primary use of the eelgrass data is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 (Figure VII-12 through VII-16). This temporal information can be used to determine the stability of the eelgrass community.

As described in the 1997 Nantucket Harbor Report, in collaboration with Charles Costello, the Nantucket Harbor Project conducted a detailed mapping of eelgrass distribution within the Harbor. Mapping was based upon both aerial photo-surveys (conducted by the MassDEP Mapping Project) and field surveys. The photo and field survey data were analyzed by Dr. Costello to develop a Harbor-wide map of eelgrass beds (Figure VII-8).

Eelgrass beds were distributed almost continuously over the lower and mid Harbor areas (Figure VII-8), but was absent from the deep basin areas, Polpis Harbor and the upper margins of Head of the Harbor. In general, where beds were present, plant density was high and the plants appeared to be healthy with little epiphyte growth. Eelgrass beds were absent in the Town region most likely due to disturbance by traffic around the Town pier and due to the channel. In the upper Harbor there were 3 areas which did not support eelgrass: the deep basin at Quaise, Polpis Harbor and Head of the Harbor (both northern shallow margin and deep basins).

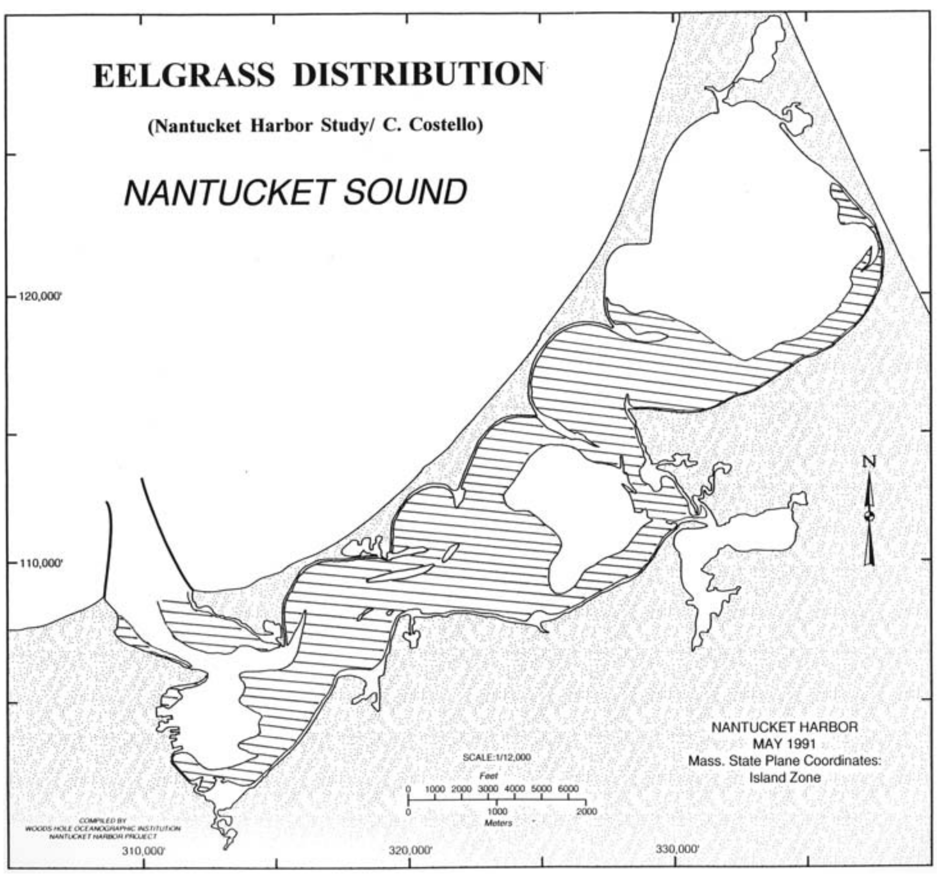


Figure VII-8. Distribution of eelgrass (*Zostera Marina*, hatched area) within Nantucket Harbor. The extensive eelgrass beds located outside the Harbor are not shown.

The loss of eelgrass coverage within the region of the Quaise basin appears to be associated with the area of deposition of organic rich sediments and deeper water. The absence of eelgrass in Quaise basin was not due to depth as sediments closer to the inlet at the same depth are colonized by luxuriant eelgrass beds. However, Quaise basin was found to receive large amounts of sinking eelgrass and some macroalgae during the scallop harvest season. It appears that disturbance of marginal beds by scallop dredges is a source of the organic matter to the basin. This deposition was observed by SCUBA divers to result in thick mats of decaying plant matter within the basin which may be affecting infauna either through smothering or secondary oxygen stress. From the available data it is not possible to determine the frequency of occurrence or longevity of the plant deposits.

The most dramatic losses of eelgrass beds were in Polpis Harbor and Head of the Harbor. In both cases shallow water areas with low water velocities were devoid of eelgrass. These regions represent a significant percentage of the overall Harbor area, and indicate an important loss of habitat for scallop recruitment. The surveys by Kelley 1982 and 1989 and the 1951 data indicate that there was eelgrass within the Eastern Basin of Polpis Harbor and that beds extended slightly more within the shallows of Head of the Harbor. In general it appears that the absence of eelgrass within the upper Harbor (Figure VII-8) is directly correlated with the distribution of sediments rich in organic matter.

Macro-algae are the large "seaweeds" which are typically seen in shallow coastal waters. Like eelgrass, macro-algae require light penetration to the bottom for growth. However unlike eelgrass, macroalgae are attached not "rooted" and continue to grow even if they become free floating. A low level of macro-algal colonization enhances the ecosystem by increasing the diversity of benthic habitat, but at high levels, macro-algal biomass can smother benthic communities and cause oxygen declines. The Nantucket Harbor Study mapped the macro-algal distribution throughout the Harbor during the late summer 1994, when biomass was at a seasonal maximum. Mapping was conducted by SCUBA divers along 58 transects (100-150m) perpendicular to shore at a separation of about 500 m. Mapping included the percent cover of each algal species and harvests of biomass.

Macro-algal abundance within the Harbor was typical of a relatively healthy environment. Algal cover was highest on the Nantucket Sound side between the points of Coatue (Figure VII-9). The highest concentrations of macro-algae were consistent with the circulation patterns associated with the cusps of land present around the Harbor edge. It also appears that the macro-algal accumulations are not related to terrestrial nitrogen inputs, since the "island" side of the Harbor, which dominates the land based loadings, had lower algal accumulations than Coatue. The species comprising the macro-algal community are also consistent with a relatively healthy environment. *Polysiphonia*, a red algae, dominated the community both in occurrence and % coverage (Table VII-2). *Codium*, a green algae, was common throughout the Harbor, although at relatively low coverage. *Codium* is an introduced species which can be a nuisance species both due to its biomass and by its attaching to hard-substrates, even scallop and oyster shells. However, this species was not found in high enough abundance to cause significant impacts to Harbor systems at present levels. Other macro-algal species were low in abundance and patchy in distribution. Overall, algal cover system-wide was low, <20% (Figure VII-10), and decreased rapidly with increasing distance from the shore. Eelgrass was found to have a higher cover within the 0-100 m transects of 30-40% compared to the about 10-20% for the macro-algae. Both the eelgrass and macro-algae were low in Polpis Harbor and the northern and eastern shores of Head of the Harbor possibly reflecting the presence of environmental stresses in those areas (Figure VII-9).

Table VII-2. Percent occurrence and percent coverage of various macrophyte species present in Nantucket Harbor.

Nantucket Harbor: Nearshore Macro-algal Species

Macrophyte	Occurrence[1] (%)	% Coverage[2] (when present)	% Coverage[3] (All: 0-100m)
Zostera	69.7	47.8	33.35
Polysiphonia	48.7	42.6	10.23
Codium	22.6	9.0	2.03
Gracilaria	5.4	7.8	0.42
Enteromorpha	4.0	11.6	0.46
Ulva	1.6	1.4	0.02
Fucus	0.2	1.0	0.00
Unvegetated[4]	12.7	---	---

[1] Percent of sampling quadrats in which macrophyte encountered.
[2] Percent coverage in Harbor areas (0-100m from shore) in which each macrophyte was found.
[3] Percent coverage of total shoreline of Harbor (0-100m).
[4] Areas devoid of vegetation within 100m of shore.

Building on the analysis of eelgrass distribution in Nantucket Harbor that was conducted in the 1997 study of the Harbor, additional eelgrass mapping was conducted by the DEP Eelgrass Mapping Program in 2001 (Figures VII-11 through VII-15). Taking all the available eelgrass data into consideration, the eelgrass surveys indicated that eelgrass habitat within this estuary is present throughout large areas of the Harbor below the sub-basin considered the Head of the Harbor yet beds are being lost from the Head of the Harbor region. The analysis of the 1951 aerial photography determined that the image quality for large areas of the Harbor was not sufficient to confidently assess the presence of eelgrass except for a small area confined to the inlet of the Harbor and Polpis Harbor, which did show the presence of eelgrass in 1951, and which was confirmed in the 1989 survey.

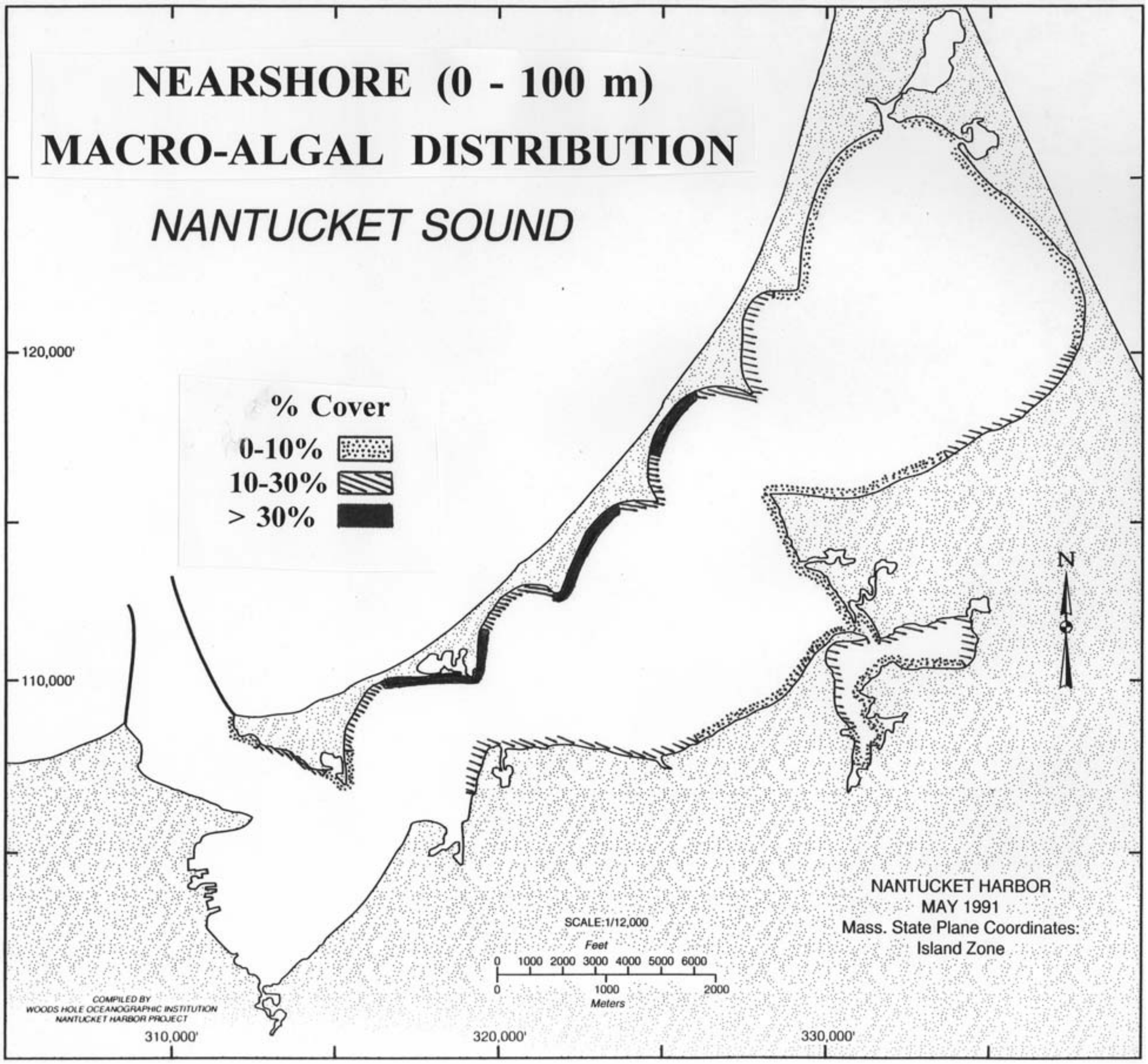


Figure VII-9. Distribution of macro-algal cover within Nantucket Harbor. The highest coverage was found along the shore of Coatue where nutrients were lowest. The distribution is consistent with patterns of water circulation.

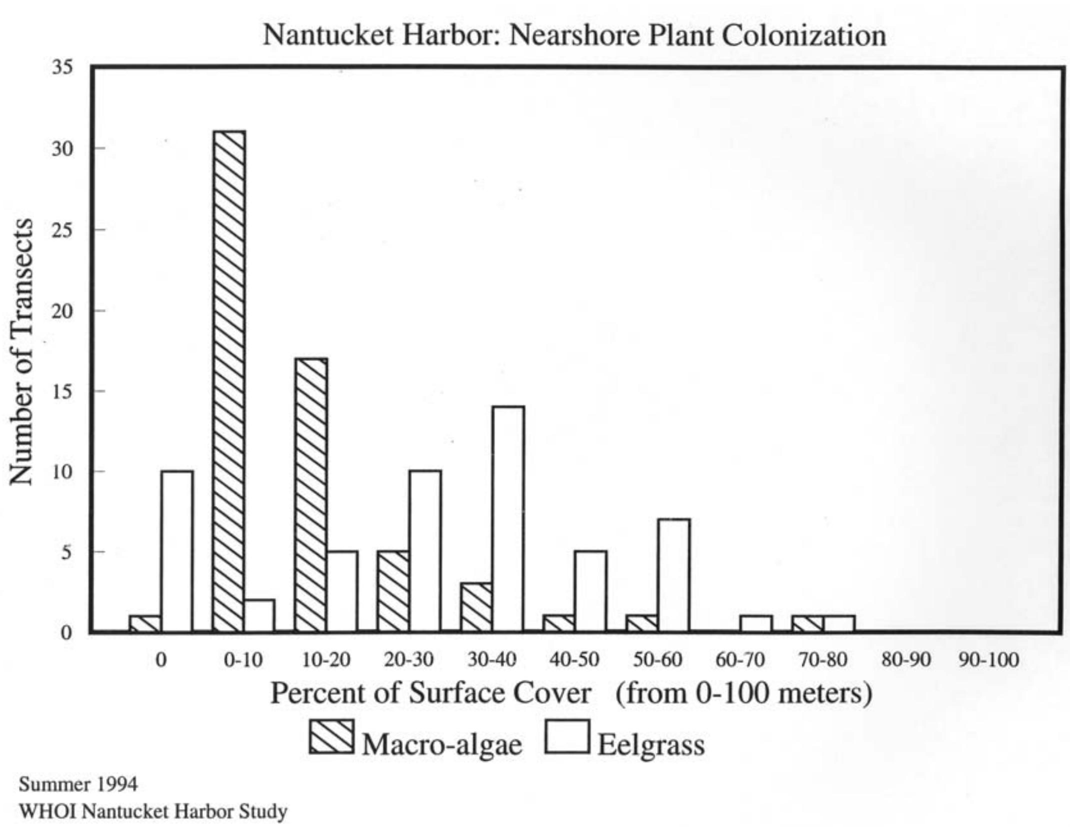


Figure VII-10. Percent of bottom area (0-100m) covered by macroalgae or eelgrass measured by shoreline survey of Nantucket Harbor during late summer/fall 1994. *Polysiphonia* and *Codium* were the predominant macroalgae encountered.

Other factors which influence eelgrass bed loss in embayments may also be at play in the Nantucket Harbor system, though the loss seems completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. First, the use of dredges in the annual scallop harvest exerts a stress on eelgrass beds both directly by scallop dredging and indirectly by creating organic matter deposits. Direct effects result from disturbance of root systems and "mowing" of shoots. While the level of this direct stress has not been quantified, the general health of the beds after years of harvests suggests that dredging in some areas is likely sustainable. However in stressed areas, it is highly probable that dredging may exacerbate bed loss and make re-colonization more difficult. The major indirect effect within the Harbor, appears to be the production of accumulations of eelgrass (and some macro-algae) biomass deposits, which cause negative impacts through smothering and generation of low oxygen conditions. Due to both direct and indirect impacts, non-disturbing scallop harvest techniques should be encouraged. Portions of the Harbor could be open to classical dredge versus non-destructive methods on an inter-annual revolving basis in order to allow additional recovery time between disturbances. This revolving approach still allows full utilization of the Harbor's scallop fishery. Disturbance to eelgrass beds can also be potentially reduced by reducing the season for scallop harvest by dredging to November-January, with non-destructive methods used February-March. At present almost 90% of the scallop landings occur before February 1 (Nantucket Harbor Study 1997). These (and other) approaches to preserving the eelgrass community upon which the scallop fishery relies need to be evaluated as to potential efficacy by the Nantucket community and appropriate technical groups (e.g. Marine Department, SHAB, etc.), before any management action is taken.

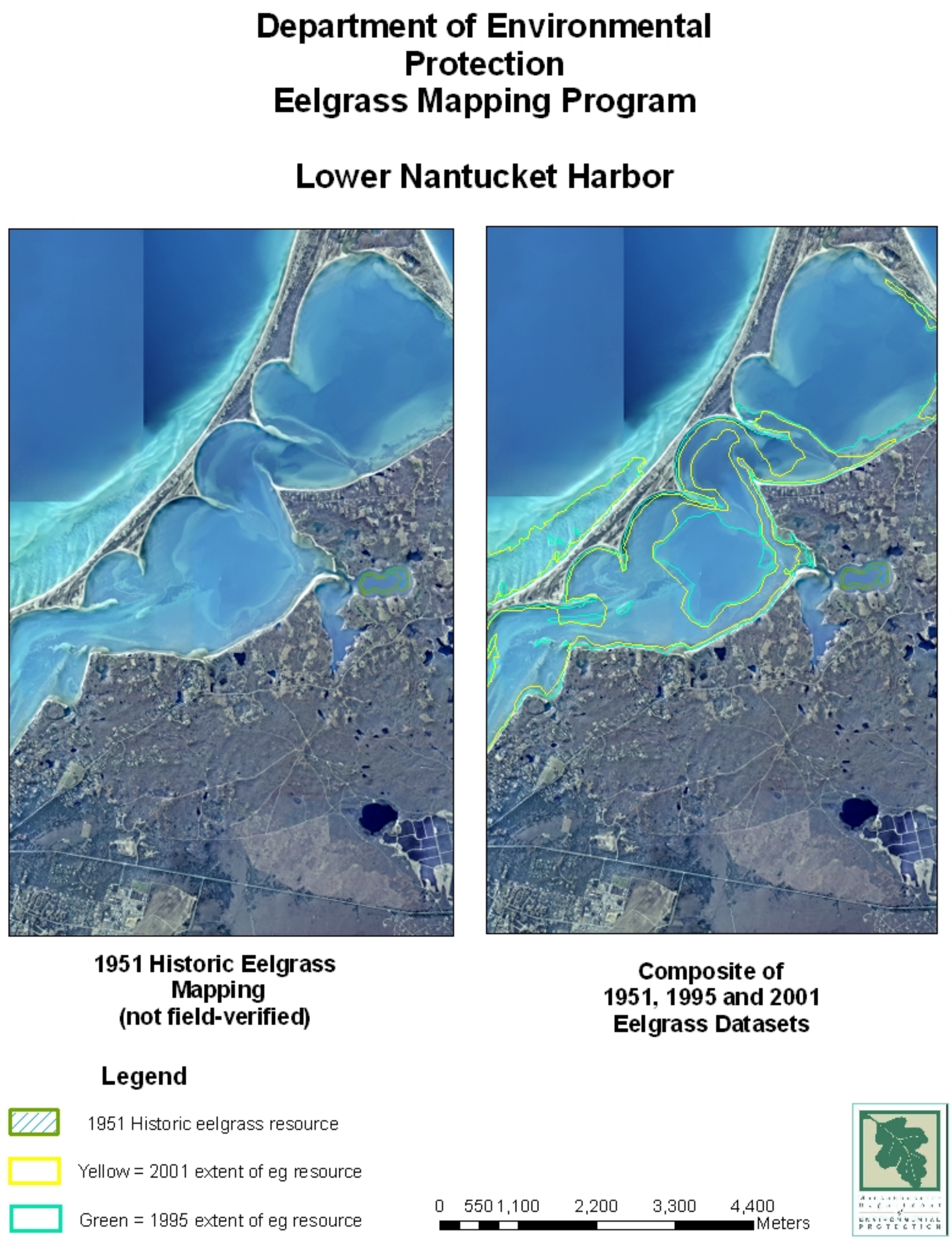


Figure VII-11. Eelgrass bed distribution within the Nantucket Harbor System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. The analysis of the 1951 aerial photography determined that the image quality for large areas of the Harbor was not sufficient to confidently assess the presence of eelgrass except for a small area confined to the inlet of the Harbor and Polpis Harbor. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were mapped by MassDEP. All data was provided by the MassDEP Eelgrass Mapping Program.

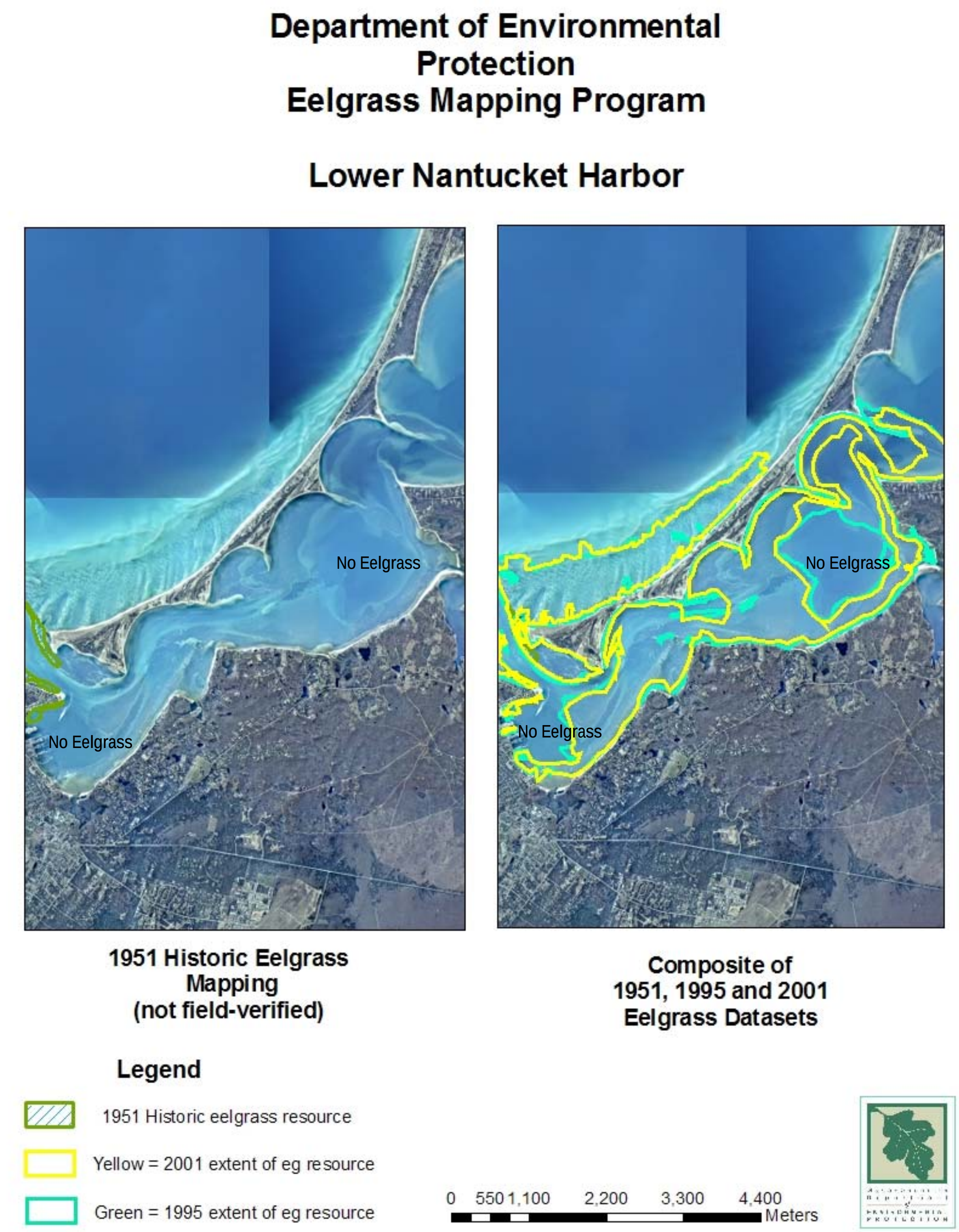


Figure VII-12. Eelgrass bed distribution within the Nantucket Harbor System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. The analysis of the 1951 aerial photography determined that the image quality for large areas of the Harbor was not sufficient to confidently assess the presence of eelgrass except for a small area confined to the inlet of the Harbor and Polpis Harbor. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were mapped by MassDEP. All data was provided by the MassDEP Eelgrass Mapping Program.

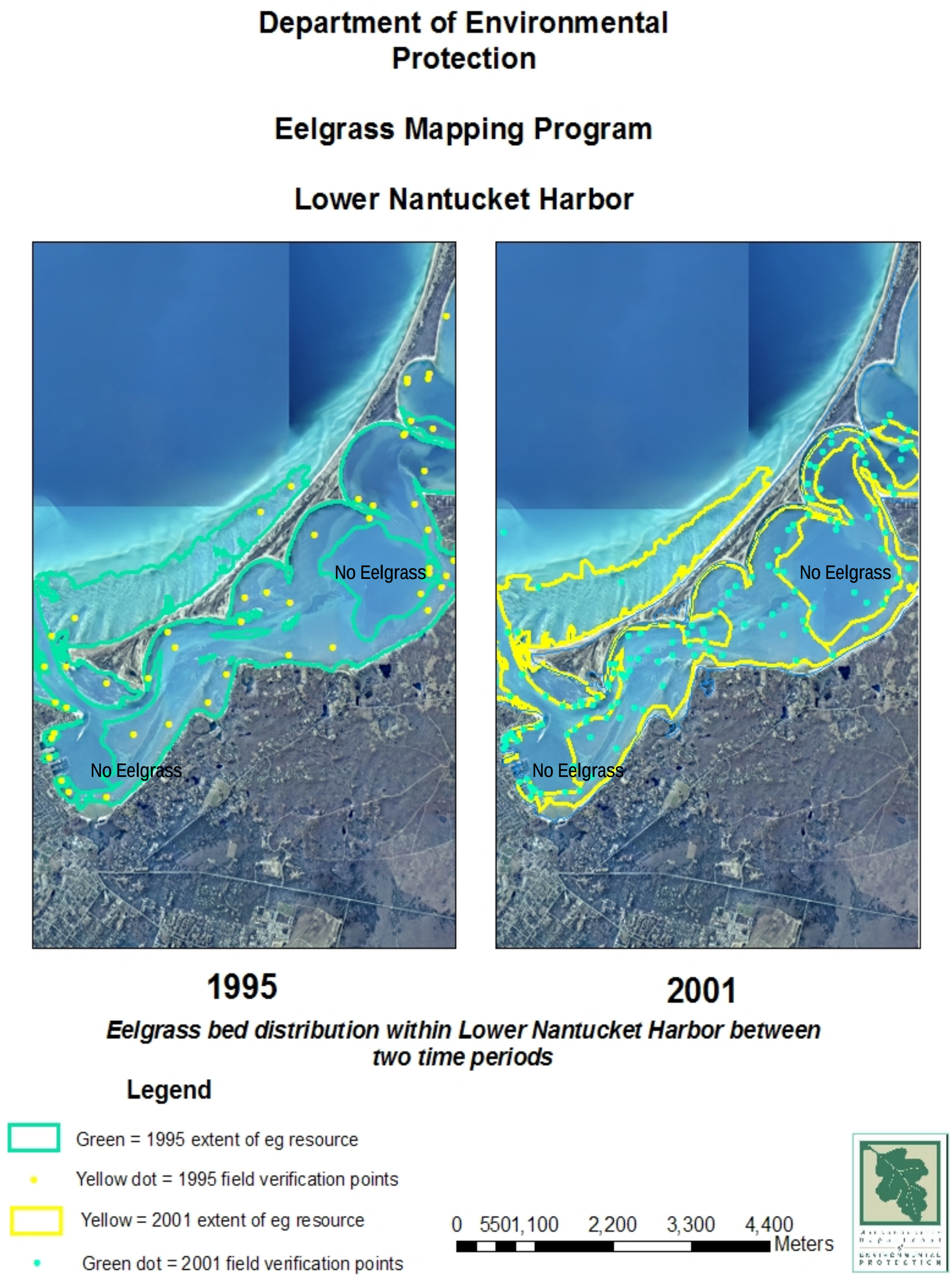


Figure VII-13. Eelgrass bed distribution within the Nantucket Harbor System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were mapped by MassDEP. All data was provided by the MassDEP Eelgrass Mapping Program.

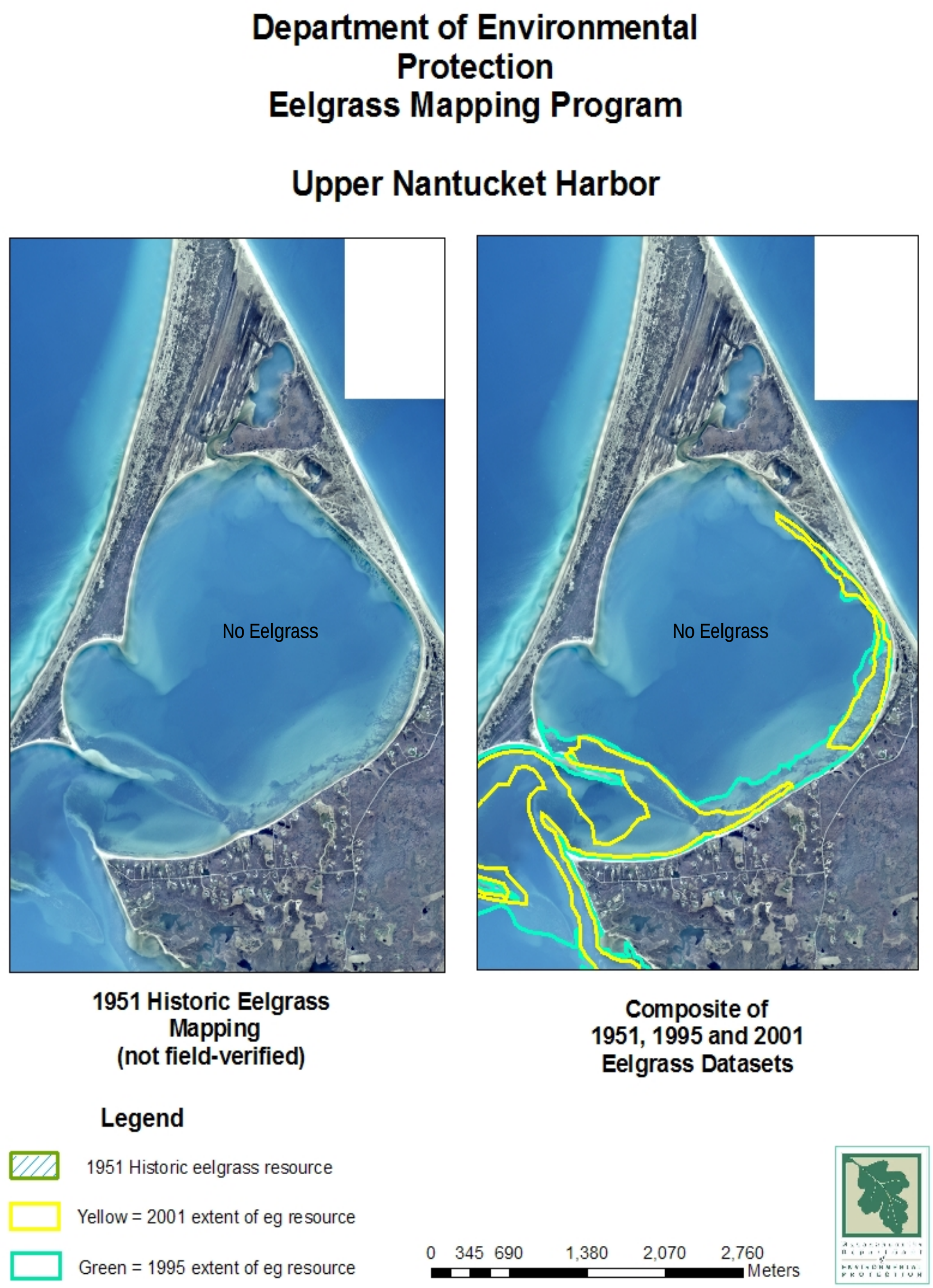


Figure VII-14. Eelgrass bed distribution within the Nantucket Harbor System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. The analysis of the 1951 aerial photography determined that the image quality for large areas of the Harbor was not sufficient to confidently assess the presence of eelgrass except for a small area confined to the inlet of the Harbor and Polpis Harbor. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were mapped by MassDEP. All data was provided by the MassDEP Eelgrass Mapping Program.

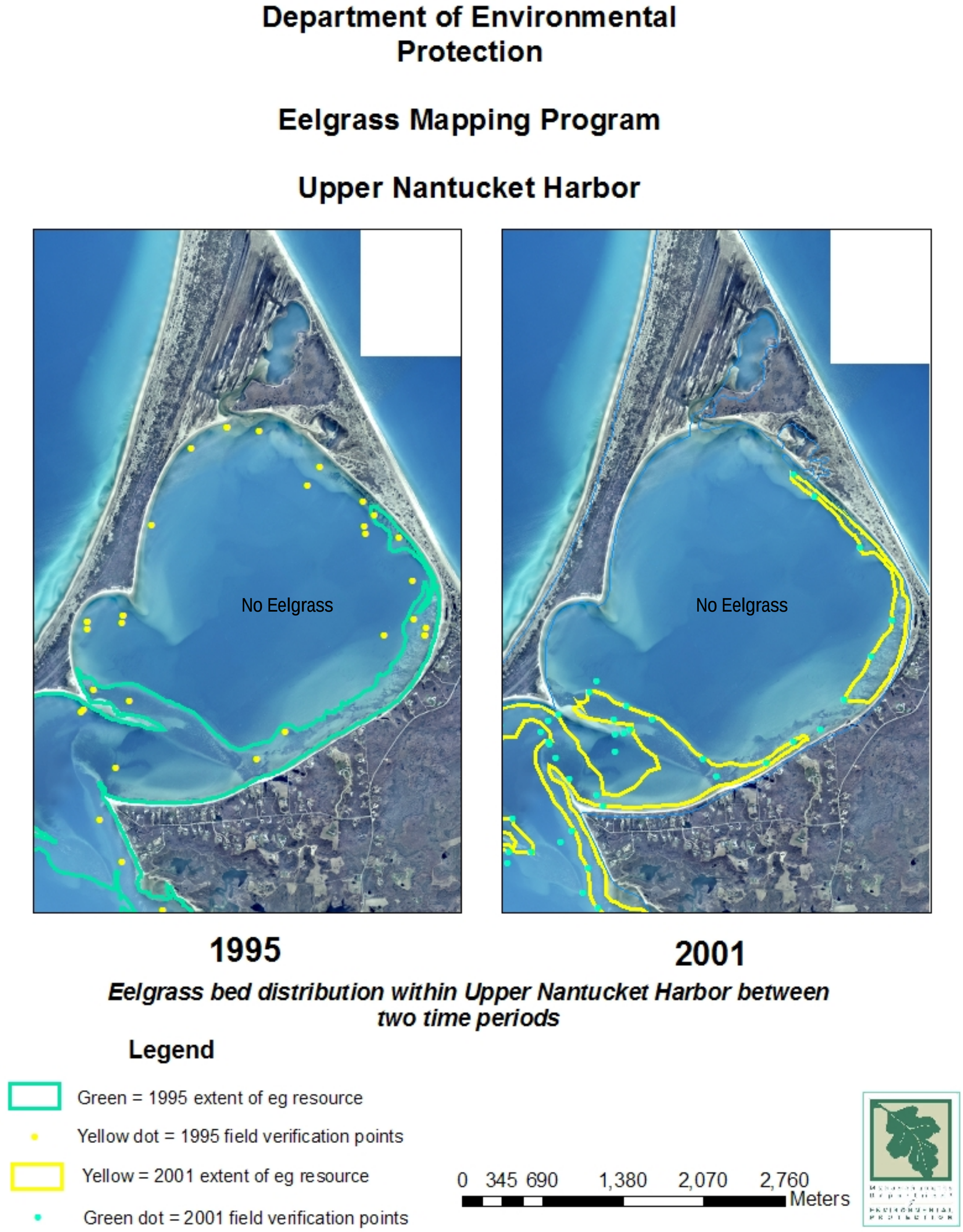


Figure VII-15. Eelgrass bed distribution within the Nantucket Harbor System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were mapped by MassDEP. All data was provided by the MassDEP Eelgrass Mapping Program.

In addition, eelgrass bed loss can be associated with moorings and docks/piers. It does not seem to be directly related to mooring density, as the Head of the Harbor sub-basin of the Nantucket Harbor system generally supports a low density of boat moorings in many of the areas where eelgrass loss has occurred. Similarly, pier construction and boating pressure may be adding additional stress but seem to be relatively minor factors in the overall system. It is not possible at this time to determine the level of direct stress that shellfishing (scallop dredging) may exert on eelgrass bed distribution or density, however, the general health of the beds as observed during the data collection effort undertaken in the 1997 Nantucket Harbor Study suggested that dredging in certain areas is likely sustainable.

Based upon all available data it appears that eelgrass is presently a widespread critical habitat within the Nantucket Harbor System. The present distribution of eelgrass results from recolonization of the Harbor from its loss in the 1930's. A map of eelgrass from the 1940's "shows it to be primarily confined to parts of the Jetties and Horse shed at the Harbor entrance (Kelley 1989). Kelley (1989) concluded that from the 1960's to 1989, "eelgrass distribution has been relatively stable in Nantucket Harbor...". Presence of zostera beds outside the mouth of Polpis Harbor is further confirmed in Lidz 1965. However, it is clear that eelgrass beds have been lost from this System. Both the MassDEP analysis and the direct observations of Kelley in 1989 indicated that there was measurable eelgrass loss. The primary location was in East Polpis Harbor. In the 1951 analysis, the east Polpis basin contained an eelgrass bed (Figure VII-11). Kelley observed eelgrass in east Polpis in 1982 but could find no eelgrass in Polpis Harbor in 1989. The other major region experiencing gradual losses is within the marginal areas of Head of the Harbor as noted by Kelley and in the MassDEP survey data. This loss appears to be gradual and occurring primarily in the least well flushed areas of this basin (note the counterclockwise circulation). Eelgrass loss has also been noted to the west of Pocomo, which was observed in the 1980 surveys and more recently in changes from 1995-2001.

The spatial pattern of bed loss is consistent with the typical pattern of habitat decline related to increasing nitrogen loading from a watershed. The pattern is for highest nitrogen levels to be found within the innermost basins, with concentrations declining moving toward the tidal inlet. This pattern is also observed in nutrient related habitat quality parameters, like phytoplankton, turbidity, oxygen depletion, etc. The consequence is that eelgrass bed decline typically follows a pattern of initial loss in the innermost basins (and sometimes also from the deeper waters of other basins). The temporal pattern is a “retreat” of beds toward the region of the tidal inlet. This appears to be the pattern of retreat observed within Head of the Harbor and Polpis Harbor (east basin). Although Nantucket Harbor generally supports healthy infaunal habitat (tolerant of higher levels of enrichment), it appears to have reached sufficient nutrient enriched to impair its eelgrass habitat. However, it is likely that if nitrogen loading were to decrease, eelgrass could be restored.

It is important to note that the nitrogen levels throughout the Nantucket Harbor System remain relatively low, consistent with the oxygen conditions, lack of macroalgae and chlorophyll a levels. However, the water depth of the Harbor and possibly vertical and horizontal mixing rates appear to have resulted in a decline in eelgrass bed coverage from the deeper areas and more enclosed basin areas. While eelgrass was recently observed within Polpis Harbor, it is presently absent at a tidally average total nitrogen (TN) level of 0.361 mg N L-1. Loss at this nitrogen level is consistent with observed losses in West Falmouth Harbor above 0.350 mg N L-1, however, given the shallower depth of Polpis Harbor, it is likely that it is just slightly above its threshold level at present. Similarly, tidally averaged levels in the lower reach of Head of the Harbor (0.340-0.353) and mid and upper reach (0.390 mg N L-1) also suggest that the recent bed losses are from a recent exceedance of the supportive nitrogen threshold. Therefore concerning eelgrass, management should focus on no net increase in nitrogen loading to the Harbor System and as possible some reduction over current loading levels.

Based on the available data, it is possible to utilize the 1995 coverage data as an indication that eelgrass beds might be recovered, if nitrogen management alternatives were implemented (Table VII-3). This determination is based upon the MassDEP Mapping Program and would indicate an area of eelgrass habitat within Nantucket Harbor of 960 acres. The relative pattern of these data is consistent with the results of the benthic infauna analysis and the observed eelgrass loss is typical of nutrient enriched shallow embayments (see below). While these numbers are approximate it does appear that the Nantucket Harbor System is at or beyond its ability to assimilate more nitrogen without further loss of eelgrass habitat.

Table VII-3. Changes in eelgrass distribution throughout the Nantucket Harbor system from 1995 to 2001. 1951 imagery was unsuitable to resolve presence or absence of eelgrass in the harbor. Data provided by Charlie Costello, DEP Eelgrass Mapping Program.

EMBAYMENT	1951 (acres)	1995 (acres)	2001 (acres)	% Difference (1995 to 2001)
Nantucket Harbor	Unmapped (imagery unsuitable for mapping)	2509.1	1551.20	38%

That the 1951 time point remain unmapped does not indicate that there was no eelgrass for that period.
The 1951 imagery in the vicinity of the inlet to the harbor was of sufficient quality to resolve the presence of eelgrass.

VII.4 BENTHIC INFAUNA ANALYSIS

Benthic animal communities are possibly the best integrators of water and habitat quality, providing information on the long-term ecological health of the Harbor system. The MEP conducted a system-wide benthic infaunal community survey to capture the range of habitat quality within the Harbor. This data builds upon the less distributed survey by the Nantucket Harbor Study which tended to focus on the deep basin areas and organic enrichment areas in Head of the Harbor and Polpis Harbor. The Harbor Study used life-history data of the various species present, their numbers and relative distribution a profile of the level of health and an indication of environmental stressors at 7 stations throughout the Harbor (Figure VII-16). Sampling was by a 25cm X 25 cm Young modified Van Veen Grab. Triplicate samples were analyzed from each location in summer (August 1992) and spring (May 1994). All of the animals (>300um) from each sample were collected and analyzed to species and each species assessed by natural history criteria as indicative of pristine, intermediate or stressed conditions.

In general, lower numbers of individuals were found in spring than summer samples, even at the control station in Nantucket Sound. This seasonal trend probably resulted from the major larval settlement occurring between the spring and summer samplings. Within Nantucket Sound, where environmental quality is high, spring and summer populations were generally the same (<25% difference). In contrast, Quaise basin, Polpis Harbor and Head of Harbor generally showed several fold shifts in population seasonally. It appears that larval recruitment is "good" Harbor wide.

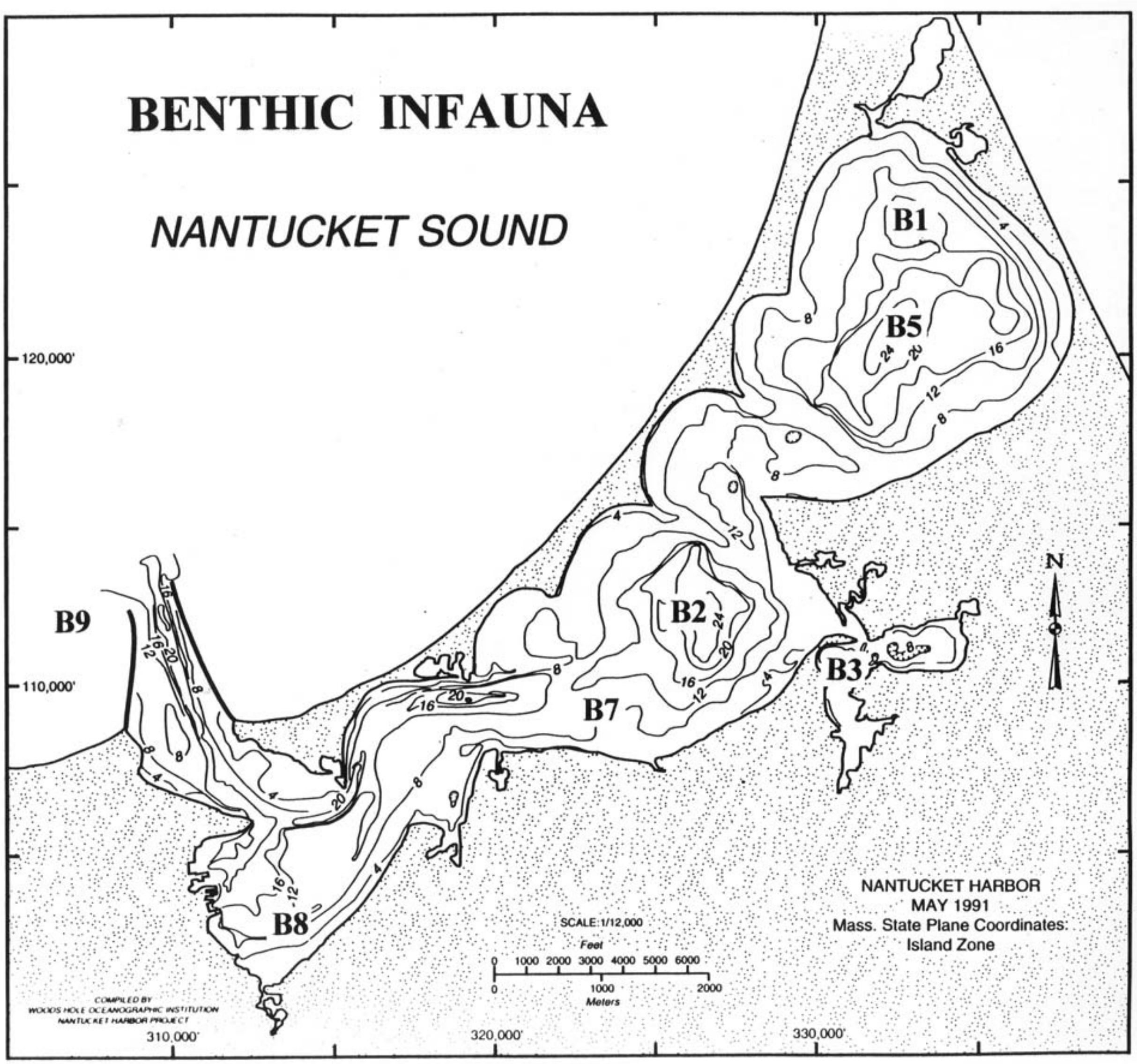


Figure VII-16. Location of sampling stations for summer 1992 (August) and spring 1994 (May) benthic infaunal surveys within Nantucket Harbor and Nantucket Sound.

There was an overall trend of lower numbers of infaunal animals in the upper Harbor regions versus the lower Harbor and offshore (Figure VII-17). In concert with the trend in animal density, was a reduction in the number of species in the lower versus upper Harbor (>30 vs. <22). The trend of decreasing animal densities moving up the estuary was matched by a shift from "pristine" indicator species (Nantucket Sound, 2nd-3rd Point) to organic enrichment indicators (Quaise basin, Polpis, Harbor Head). Stress indicator species were not generally found within the Harbor system. The upper Harbor and Polpis Harbor which were dominated by species indicative of organic matter enrichment were primarily inhabited by amphipods (e.g. *Ampelisca*) and small polychaete and oliochaete worms. In these regions generally 90% of the individuals were represented by 4 or less species. In contrast, within the lower Harbor and Nantucket Sound stations, 90% of the individuals are distributed among more than 10 species (Table VII-4). In addition, the more diverse lower Harbor regions were dominated by mollusks (bivalves and gastropods) and larger polychaete worms. Many of the species within the lower Harbor are important to fisheries, almost all are indicative of high quality habitat.

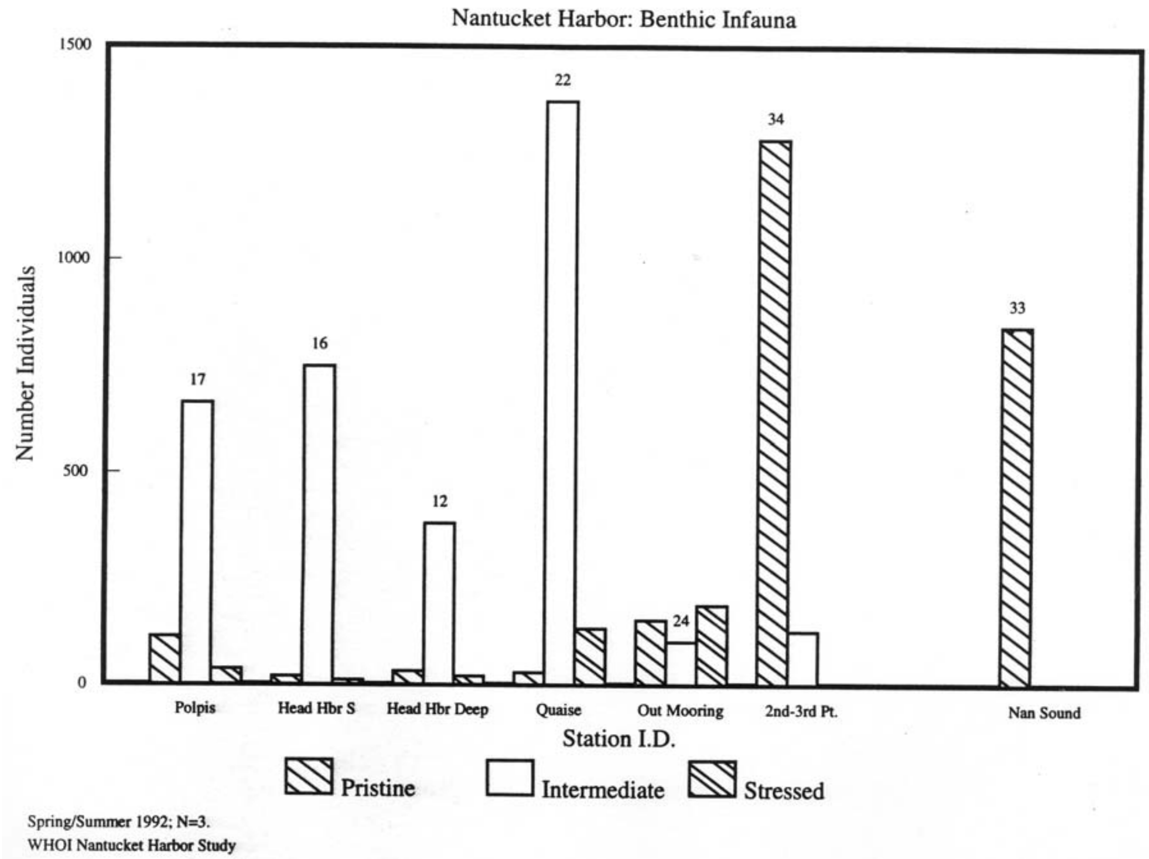


Figure VII-17. Number of individuals per 0.04 m^2 of benthic animal species representative of pristine, intermediate and stressed environmental conditions. Numbers of bars represent number of species present at each station. Note the shift from pristine to intermediate conditions between the lower and upper portions of the Harbor.

The density and diversity of the benthic animal communities and the distribution of indicator species was used to chart the habitat quality within the Harbor (Figure VII-18). The areal coverage is based upon the depth contours and SCUBA diver visual surveys reporting on the homogeneity of the bottom within each basin. In general, most of the bottom within the Harbor can be classified as high quality habitat. However, Polpis Harbor, Quaise Basin and Head of the Harbor exhibited Moderate to Low quality conditions. The region of the Town Basin pier area was also of low to moderate quality. In all cases the low quality habitat was associated with the basins where organic deposition was high and the eelgrass beds have disappeared. Also, in the deeper basins (e.g. Quaise) the periodic accumulation of mats of eelgrass and macro-algal debris certainly contributes to the stress to animal communities. The increase in low-moderate quality area from the lower to the upper Harbor parallels the observed nutrient gradient and is consistent with the more than 2 fold higher rates of oxygen consumption (organic matter decay) in the less flushed upper Harbor regions. Taken as a whole the Harbor Study infaunal survey suggests a common environmental stressor associated with the low and moderate quality regions. The patchy distribution of stress throughout the Harbor supports the contention that the stress is not a toxic contaminant, but more likely related to nutrient and organic matter cycling. The seasonal shifts in population density within the upper Harbor regions are consistent with periodic oxygen depletion, a condition which is exacerbated by increased levels of nitrogen loading.

Table VII-4. Benthic infaunal community data (Fall 2003) for the Nantucket Harbor system by component sub-embayment (Head of Harbor, Quaise Basin, Town Basin, Polpis Harbor). 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). Station ID's refer to Figure VII-19.

Sub-Embayment	Location	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Head of the Harbor						
Upper-Shallow	Sta. 17A	20	442	16.6	3.80	0.88
	Sta. 17B	13	496	12.2	3.26	0.88
Coatue-Shallow	Sta. 14A	14	554	12.4	3.13	0.82
	Sta. 14B	6	160	6.0	2.32	0.90
Wauwinet	Sta. 15A	9	200	8.9	2.91	0.92
	Sta. 15B	19	699	11.5	2.80	0.66
Mid-Deep	Sta. 16A	14	224	13.1	3.31	0.87
	Sta. 16B	10	160	9.7	2.73	0.82
Quaise Basin						
Pocomo Pt	Sta. 13A	27	351	16.9	3.25	0.68
	Sta. 13B	15	359	11.8	2.57	0.66
Coatue-Shallow	Sta. 7A	16	760	13	3.12	0.78
	Sta. 7B	10	109	10	2.78	0.84
Mid-Shallow	Sta. 9A	13	72	NA	3.06	0.83
	Sta. 9B	13	380	10.7	2.82	0.76
	Sta. 6A	19	282	12	2.49	0.59
	Sta. 6B	16	120	13	3.04	0.76
	Sta. 5A	11	22	NA	3.12	0.90
	Sta. 5B	16	145	13	2.73	0.68
Mid-Deep	Sta. 8A	14	288	12	2.79	0.73
	Sta. 8B	7	160	7	2.38	0.85
Town Basin						
	Sta. 4A	22	583	8	1.55	0.35
	Sta. 4B	12	428	9	2.40	0.67
	Sta. 2A	20	320	16	3.16	0.73
	Sta. 2B	14	150	12	2.88	0.76
	Sta. 3A	29	176	21	4.01	0.83
	Sta. 3B	26	299	15	3.25	0.69
Polpis Harbor						
East	Sta. 12A	11	560	9.5	2.47	0.71
	Sta. 12B	9	204	8.2	2.19	0.69
West Upper	Sta. 11A	9	104	9.0	3.03	0.95
	Sta. 11B	12	133	11.4	2.97	0.83
West Lower	Sta. 10A	19	444	15.2	3.34	0.79
	Sta. 10B	14	88	14.0	3.55	0.93

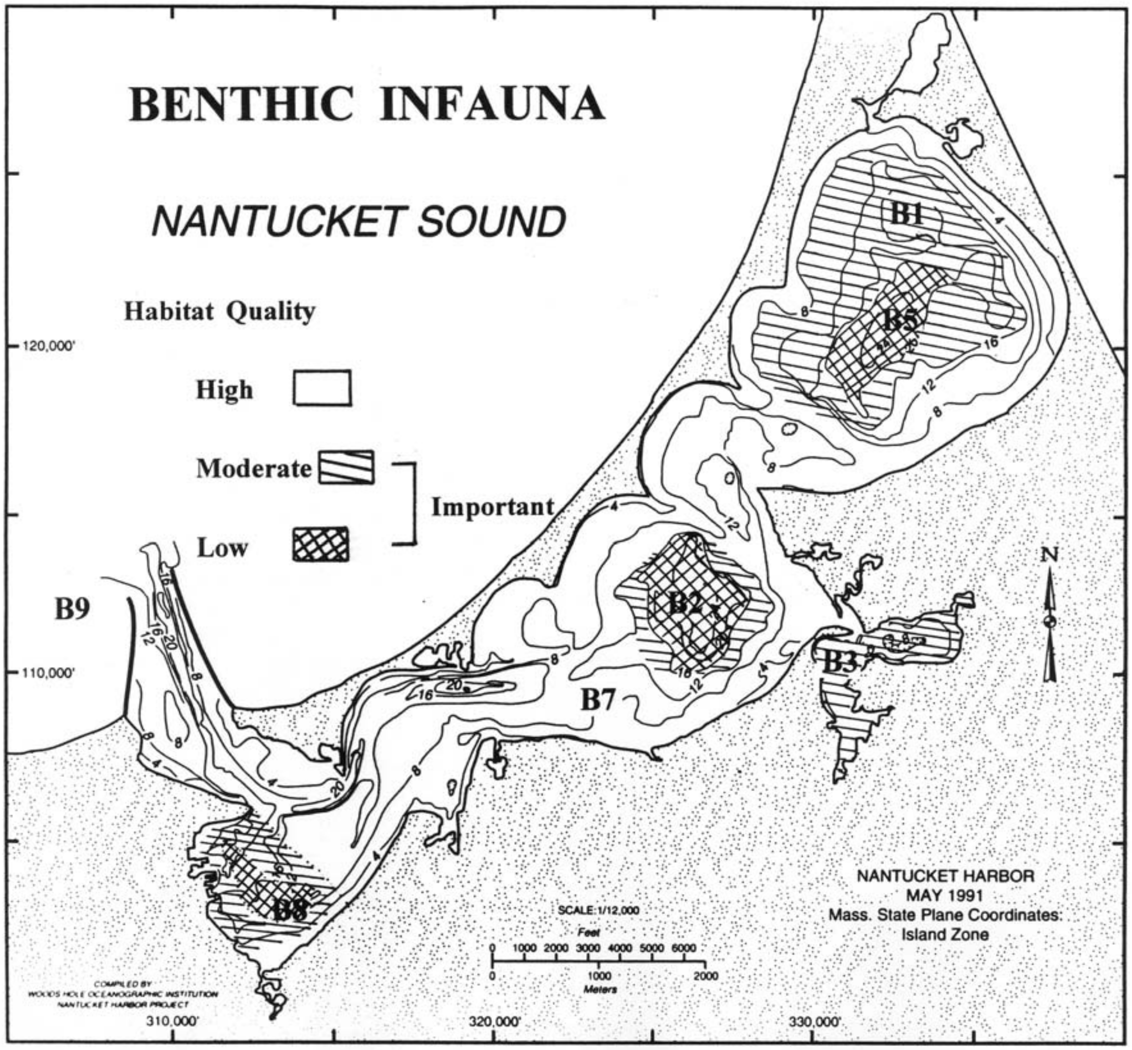


Figure VII-18. Distribution of high, moderate and low benthic habitat quality areas based on summer 1992 and Spring 1994 infaunal surveys. Areal coverage incorporated data from visual diver surveys, sediment type and organic matter content as well as basin configuration.

The MEP Technical Team conducted an additional quantitative survey in October 2003 at 17 stations in the Nantucket Harbor System, with 3 of the 17 sites being located within Polpis Harbor (Figure VII-19). Unlike the Harbor Study which tended to focus on the more enriched sites and documented that the deep basin regions were organically enriched and supported species typical of organic sediments and tolerant of systems with periodic oxygen depletions, the MEP survey was aimed at assessing the general conditions of each basin. In all areas and particularly those 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 the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the loss of eelgrass beds in the Head of the Harbor sub-basin and thinning in other areas, the Nantucket Harbor System is showing signs of being impaired by nutrient overloading. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

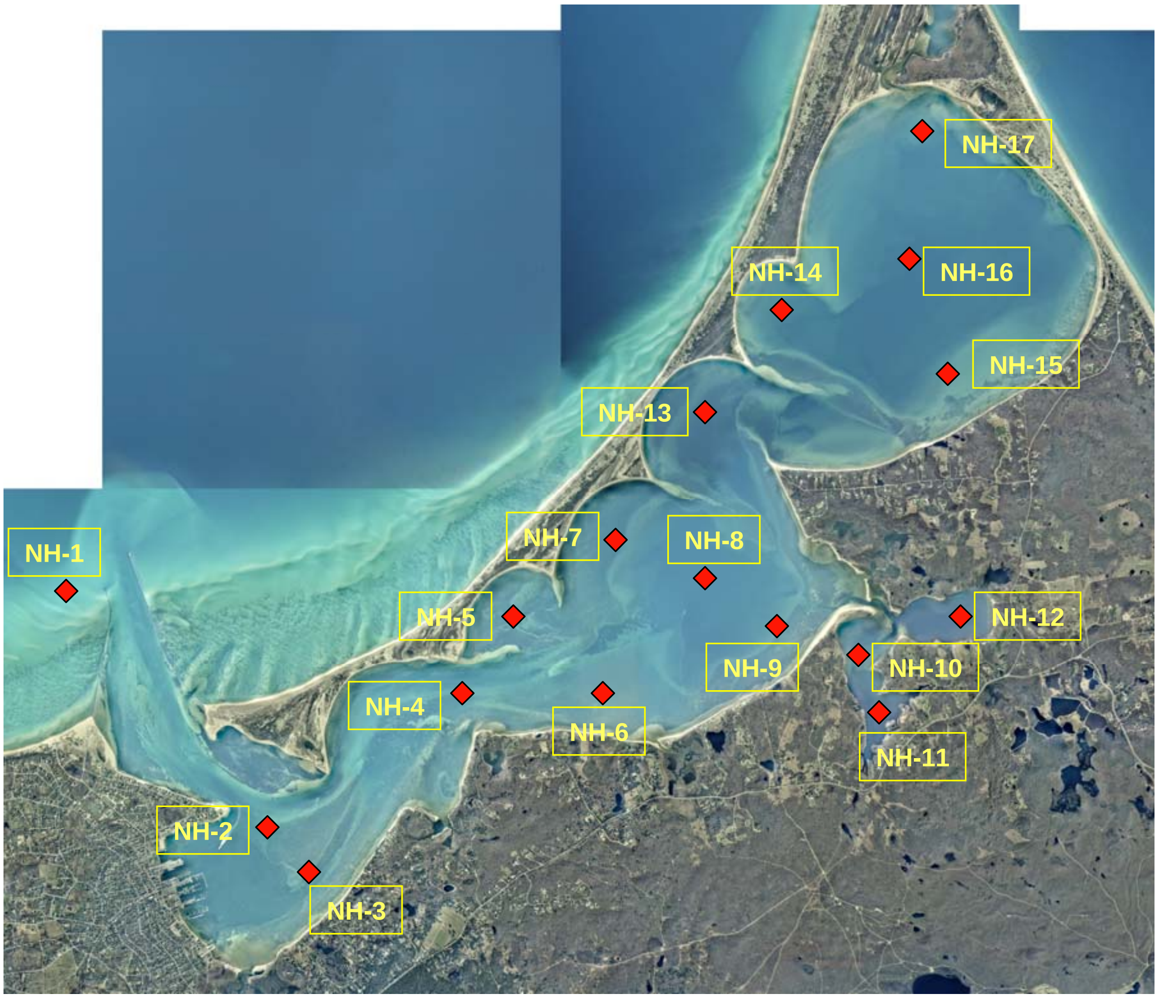


Figure VII-19. Aerial photograph of the Nantucket Harbor system showing location of benthic infaunal sampling stations (red symbol). Infaunal samples collected in the fall of 2003.

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

The MEP infaunal study indicated that the lower basins and shallower areas (<12') areas of the main Harbor basins generally support high quality infaunal habitat. The lowermost basin

(Town) exhibited a dense, highly diverse and relatively evenly distributed community, with some variation. The shallower margins of both Quaise and Head of the Harbor were only slightly less diverse than areas nearer the tidal inlet, but were clearly indicative of high quality. This is further evidenced by the growth of epibenthic scallops in these areas. Within the main Harbor basins, only the deep "holes" showed reduced numbers of species and individuals and organic enrichment indicators. This indication of moderate to poor habitat in these deep regions is consistent with the previous analysis and supported by the observed accumulations of organic detritus in these natural depositional areas. It is unlikely that management of nitrogen loading will be able to create significant improvement within these deep basin regions and it is likely that these areas have been "stressed" by natural processes for a long time.

Both the MEP and Harbor Study surveys found Polpis Harbor to be supportive of both moderate to large numbers of species and individuals of diverse and even distribution. However, both studies found the habitat in both the east and west basins to be dominated by productive communities dominated by organic matter enrichment indicators, presently *Mediomastus*. It is likely that this community is structured by the enclosed nature of Polpis Harbor, which results in enrichment of nitrogen and organic matter and deposition to the sediments. However, the benthic community is clearly productive and diverse and therefore, for its local environment appears healthy.

Overall, the MEP system-wide survey found higher numbers of species and individuals in communities that were generally more diverse and evenly distributed than the other 20 embayments examined to date by the MEP in southeastern Massachusetts. This is consistent with the relatively low tidally averaged nitrogen levels within the system, <0.40 mg N L-1. It should be noted that this upper limit of the Nantucket Harbor System nitrogen level, compares well to the levels to support healthy infauna found in West Falmouth Harbor (main basin) of 0.38 mg N/L and in enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg N/L were found to be supportive of healthy infaunal habitat. All of these results are integrated into the assessment of habitat quality throughout the Nantucket Harbor System relative to nitrogen levels in Chapter VIII. It appears that the primary habitat concern for the Nantucket Harbor System is the present decline in eelgrass coverage.

The overall results indicate a system generally supportive of diverse healthy communities relative to each of the 3 component basin types. The infaunal habitat quality within each of the basins of the Nantucket Harbor System is fully consistent with the oxygen measurements (Section VII.2), temporal trend in eelgrass (i.e. only recent loss from outer basin) and relatively low tidally averaged total nitrogen concentration for each basin. These levels compare well to the levels to support healthy infauna found in West Falmouth Harbor (main basin) of 0.38 mg N/L and in enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg N/L were found to be supportive of healthy infaunal habitat. All of these results are integrated into the assessment of habitat quality throughout the Nantucket Harbor System relative to nitrogen levels in Chapter VIII.

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll-a). Additional information on temporal changes within each sub-embayment and its associated watershed nitrogen load further strengthen the analysis. These data were collected to support threshold development for the Nantucket Harbor System by the MEP Team and were discussed in Chapter VII and summarized in Table VIII-1. 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 the Town of Nantucket with technical support from the Coastal Systems Program at SMAST and others.

Nantucket Harbor is a complex estuary comprised of a large lagoon, Nantucket Harbor, running parallel to the barrier beach, and smaller enclosed drowned river valley estuary, Polpis Harbor, which is shallow and supports salt marsh along much of its margin. The Nantucket Harbor Estuary formed primarily through the gradual expansion of the barrier beach, Coatue Spit. As an embayment to Nantucket Sound, Nantucket Harbor receives high quality low nutrient flood waters, but by its physical structure supports the enrichment of its basin waters from nitrogen input from the atmosphere and watershed. The morphology of the sub-basins comprising this System, contain deep regions (Quaise, Head of the Harbor) and are enclosed (Polpis Harbor), increasing their susceptibility to the negative impacts from nutrient loading. However, much of the lower Harbor region, between Quaise and the inlet, is well flushed and presently exhibits high habitat quality. Determining the appropriate nitrogen management threshold for the Nantucket Harbor System must take into account both the natural processes and differing sensitivities of its various component sub-basins. In addition, evaluation of the deep regions of Quaise and Head of the Harbor basins must take into account their depositional nature, periodic stratification and low oxygen conditions resulting from either natural or human inputs.

Evaluation of habitat quality must consider the natural structure of each system and the types of eelgrass habitat and infaunal communities that they naturally support. At present, the Nantucket Harbor System is showing variations in nitrogen enrichment among its 4 principal component basins. The inner basins of Head of the Harbor and Polpis Harbor are nitrogen enriched over Quaise and the Town basins. Although the component basins of the Nantucket Harbor System are clearly enriched in nitrogen over the adjacent Nantucket Sound waters, the enrichment is relatively small, generally <0.100 mg L^{-1} (see Chapter VI). The evaluation of habitat quality within each of these 4 basins was based upon the level of nitrogen enrichment, resultant oxygen depletion and chlorophyll enhancement and eelgrass and infaunal indicators relative to ecology of each specific basin.

Like many estuaries where the greatest nitrogen enrichment and impairment is in the inner basins, the overall results of the MEP threshold analysis for Nantucket Harbor indicate infaunal communities in all basins are healthy or relatively healthy. The infaunal communities in this System are generally more productive, diverse and evenly distributed than the other 20 embayments examined to date by the MEP in southeastern Massachusetts. The "impaired" infaunal habitat within the deep regions of the Quaise and Head of Harbor basins appear to derive from basin structure (settling basins) and resultant organic matter deposition and oxygen depletion. It appears that the primary habitat concern for the Nantucket Harbor System relates to eelgrass habitat. Impairment of eelgrass habitat is seen in the present decline in eelgrass coverage in the shallow margin of Head of the Harbor basin and the loss of beds within Polpis Harbor (Table VIII-1). The eelgrass loss in Polpis Harbor (east basin) would indicate a significant to moderate impairment of this sub-system and the declining coverage in Head of the Harbor would classify that basin as moderately impaired. The other regions of the Nantucket Harbor are currently displaying healthy habitats or natural conditions (e.g. deep regions of deep basins). The west basin of Polpis Harbor, which has no historic documentation of supporting eelgrass is therefore classified as supporting relatively healthy (lower reach) and moderately healthy (upper reach) infauna habitat. However, the infaunal communities in Polpis Harbor are consistent with the organically enriched nature of that system, which receives surface water discharge from wetlands and supports salt marsh along its margins.

Eelgrass: Based upon all available data it appears that eelgrass is presently a widespread critical habitat within the Nantucket Harbor System. The present distribution of eelgrass results from recolonization of the Harbor from its loss in the 1930's. A map of eelgrass from the 1940's "shows it to be primarily confined to parts of the Jetties and Horse shed at the Harbor entrance (Kelley 1989). Kelley (1989) concluded that from the 1960's to 1989, "eelgrass distribution has been relatively stable in Nantucket Harbor...". However, it is clear that eelgrass beds have been lost from this System. Both the MassDEP analysis and the direct observations of Kelley in 1989 indicated that there has been measurable eelgrass loss. The primary locations are within Head of the Harbor and East Polpis Harbor. In the 1951 analysis, the east Polpis basin contained an eelgrass bed (Figure VII-12). Kelley observed eelgrass in east Polpis in 1982 but could find no eelgrass in Polpis Harbor in 1989. The other major region experiencing gradual losses, the marginal areas of Head of the Harbor, is supported by both Kelley (1989) and the MassDEP survey data. This larger areal loss appears to be gradual and occurring primarily in the least well flushed areas of this basin (note the counterclockwise circulation). Eelgrass loss has also been noted to the west of Pocomo, which was observed in the 1980 surveys and more recently in changes from 1995-2001. It is important to note that the eelgrass bed loss is both from the shallow area of the upper and mid regions of Head of the Harbor (<8' depth) and from the "deeper" areas (8'-12') in the lower reach and from the shallow east basin of Polpis. The data indicate that that on the order of 1000 acres of eelgrass habitat within the Nantucket Harbor System is impaired.

Macro-algal abundance within the Harbor surveyed in 1994 (Harbor Study 1997) was typical of a relatively healthy environment. Algal cover was highest on the Nantucket Sound side between the points of Coatue (Figure VII-10). The highest concentrations of macro-algae were consistent with the circulation patterns associated with the cusps of land present around the Harbor edge. It also appears that the macro-algal accumulations are not related to terrestrial nitrogen inputs, since the "island" side of the Harbor, which dominates the land based loadings, had lower algal accumulations than Coatue. The absence of macroalgal accumulations and drift algae is consistent with the generally low nitrogen levels throughout this System and the relatively low watershed nitrogen input.

The spatial pattern of bed loss is consistent with the typical pattern of habitat decline related to nitrogen loading. The pattern is for highest nitrogen levels to be found within the innermost basins, with concentrations declining moving toward the tidal inlet. This pattern is also seen in the other nutrient related habitat quality parameters, like chlorophyll, turbidity, oxygen depletion, etc. The consequence is that eelgrass bed decline typically follows a pattern of initial loss in the innermost basins and from the deeper waters. The temporal pattern is a “retreat” of beds toward the region of the tidal inlet. This appears to be the pattern of retreat observed within Head of the Harbor and Polpis Harbor (east basin). Although Nantucket Harbor generally supports healthy infaunal habitat (tolerant of higher levels of enrichment), it appears to have reached sufficient nutrient enriched to impair its eelgrass habitat. However, it appears that this System is just over its nitrogen assimilative capacity (nitrogen threshold), as it still supports significant eelgrass habitat. Being just at or over its threshold makes it likely that if nitrogen loading were to decrease, eelgrass could be restored.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Nantucket Harbor Estuarine System on Nantucket Island within the Town of Nantucket, MA., based upon assessment data presented in Chapter VII. The bilobate Polpis Harbor is an enclosed sub-system tributary to the Quaise basin.

	Nantucket Harbor Estuarine System				
Health Indicator	**Head of Harbor**	**Quaise**	**Town Basin**	**Polpis Harbor**	
				East	**West**
Dissolved Oxygen	H[2]/MI[1]	H[2]/MI[1]	H[2]	H/MI[3]	H/MI[3]
Chlorophyll	H[6,7]	H[6,7]	H[6,7]	H[6,7]	H[6,7]
Macroalgae	--[4]	--[4]	--[4]	--[4]	--[4]
Eelgrass	MI[13]	H	H	SI[12]	--[11]
Infaunal Animals	H[8]/MI[9]	H[8]/MI[9]	H[5]	H/MI[10]	H/MI[10]
Overall:	**H[8]/MI[9]**	**H**	**H**	**MI[14]**	**H/MI**

1 – in the deep basins oxygen depletions periodically 4-5 mg/L., generally >5 mg/L.
2 -- in the large moderate/shallow areas accounting for most of the basin region, oxygen levels generally > 6 mg/L with occasional depletions to between 6-5 mg/L
3 – oxygen depletions periodically to 4.5-6 mg/L, generally above 6 mg/L.
4 – very sparse or absence of drift algae based upon Nantucket Harbor Study Survey
5 – generally high diversity, high numbers, eveness generally $\geq$0.7.
6 -- based upon limited monitoring grab sample data.
7 -- secchi depth generally to bottom in Polpis, averaging 2.3-2.6 in main Harbor basins
8 – extensive shallow areas generally moderate-high numbers of individuals and species, eveness generally high.
9 -- deep region of basin diminished numbers of individuals and species, with some organic matter enrichment indicators.
10 -- moderate numbers of species and individuals, but high diversity and eveness, enrichment indicator - *Mediomastus* dominant.
11 – no evidence this basin is supportive of eelgrass.
12 -- historical eelgrass beds lost
13 -- some gradual decline in distribution of historical eelgrass beds
14 -- based upon eelgrass loss

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

It is important to note that the nitrogen levels throughout the Nantucket Harbor System remain relatively low, consistent with the observed oxygen conditions, lack of macroalgae and chlorophyll a levels. However, due to the water depth in the Harbor, it is possible that vertical and horizontal mixing rates appear to have resulted in a decline in eelgrass bed coverage from the deeper areas and more enclosed basin areas. While eelgrass was recently within Polpis Harbor, it is presently absent at a tidally average total nitrogen (TN) level of 0.361 mg N L-1. Loss at this nitrogen level is consistent with observed losses at generally similar depths in West Falmouth Harbor above 0.350 mg N L^{-1} and observed losses in Phinneys Harbor at 0.36 mg N L^{-1}. However, given the shallower depth of Polpis Harbor, it is likely that it is just slightly above its threshold level at present, since shallower waters can generally support eelgrass at slightly higher nitrogen levels than deeper waters. Similarly, tidally averaged levels in the lower reach of Head of the Harbor (0.340-0.353) and mid and upper reach (0.390 mg N L-1) also suggest that the recent bed losses are from a recent exceedance of the supportive nitrogen threshold. The data indicate that eelgrass habitat within the inner basins of the Nantucket Harbor System are impaired, being at or beyond their ability to assimilate more nitrogen without further loss of eelgrass beds. The Head of the Harbor basin is clearly moderately impaired for eelgrass, due to the documented loss of eelgrass coverage, but the continued presence of eelgrass in the marginal areas and in the lower reach would indicate the possibility for restoration of these marginal beds with future decreases in nitrogen load to this basin. The east basin of Polpis Harbor is presently significantly impaired, as it supported a significant eelgrass bed in 1951 and some eelgrass in 1982 and 1989, but no longer supports eelgrass. The west basin of Polpis Harbor does not have a record of eelgrass. Both Polpis Basins support infaunal communities commensurate with the nature of the enclosed basins and their association with wetlands. Therefore, it is clear that resource management should focus on eelgrass habitat and on preventing further increase in nitrogen levels and as possible some reduction over current loading levels.

Water Quality: 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 these excursions are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 3.8 mg L^{-1}.

Within the highly flushed and generally well mixed waters of the lower basins of Nantucket Harbor, bottom waters were well oxygenated (>6mg L^{-1}). The few excursions below 6 mg L^{-1} were isolated events, rather than a prolonged depletion such as generally associated with a phytoplankton bloom. However, these variations were small and overall the oxygen conditions are consistent with the observations of healthy infaunal and eelgrass communities. While Polpis Harbor also exhibited well oxygenated conditions, larger diurnal variations were recorded than in the outer basins. The higher diurnal fluctuations indicate waters supporting higher phytoplankton biomass. The lack of a low oxygen event is likely the result of the lack of watercolumn stratification within this shallow system.

Quaise basin showed both significant diurnal oxygen fluctuations and an overall oxygen decline, although not to levels of high stress. There was a single "event" of a few days when each night oxygen levels reached 4 mg/L, but returned to ~5 mg L^{-1} each following day. Since the meter was located deeper within the basin (~6 m), oxygen levels throughout most of the basin area were almost certainly higher given their shallower depths, only in the "deep hole" was oxygen depletion likely greater. Assessing oxygen conditions within the Quaise basin indicates generally non-stressful oxygen levels, except for the deep basin. However, it is likely that the presence of the deep hole (~30') creates a geomorphological (natural) cause of the low dissolved oxygen, as it creates a depositional area and is susceptible to periodic watercolumn stratification. The depositional nature of the basin results in large accumulations of eelgrass detritus in the late fall and early spring. It is likely that a major function of these periodically deposited mats is to smother the infaunal communities at the bottom of the "hole", as the surficial sediments beneath them were observed to lack a surface oxygenated layer with hydrogen sulfide reaching the sediment/water interface. There is evidence that the mats are transitory and do not occur each year. Their deposition is likely mediated by water circulation which is both tidally and storm driven in this system. It should be noted that these large deposition events are not related to nitrogen loading of the Harbor System.

Similarly, Head of the Harbor showed generally high oxygen levels. As in the Quaise basin, the meter was deeper in the basin and observed oxygen depletions were greater than experienced by bottom waters throughout most of the basin area. The oxygen conditions are consistent with the observed distribution of habitat quality throughout the Harbor System, with the deep waters showing oxygen depletion, but with oxygen levels generally supportive of a high habitat quality for infauna. However, since the system does show oxygen levels less than full atmospheric saturation, additional organic matter loads, (e.g. through nitrogen inputs) will likely increase the magnitude and frequency of the oxygen declines, again indicating a system at or just beyond its nitrogen assimilative capacity (nitrogen threshold).

The oxygen records from the moored instrumentation are consistent with the results from the periodic grab samples by the water quality monitoring programs. While grab samples are not necessarily a good indication of the degree of oxygen depletion in embayment waters, given the potential temporal variation, the data can be used if there are sufficient numbers of sampling dates. Given the 81 sampling dates in Nantucket Harbor from 1988-2005, an analysis was conducted by the MEP Technical Team. This analysis confirms the results of the mooring data. At all stations and dates throughout the Nantucket Harbor System, only a single sample was found to be <4 mg L^{-1} and that was from the deep water in the Head of the Harbor basin (7 m, 3.68 mg L^{-1}) in 1993. The next lowest value recorded in the System was 4.4 mg L^{-1}. In Quaise and the Town there were only 5 and 8 samples <6 mg L^{-1}, with the only 1 sample < 5 mg L-1 (4.81 mg L^{-1}). Polpis Harbor showed slightly more frequent, but still only moderate depletions, with the in the East and West basins having 4 and 3 dates between 4.4-5.99 mg L-1 and a total of 12 dates <6 mg L^{-1}. These data support the contention that except in the deep holes of the main Harbor, oxygen depletion is generally only short term and moderate, with the overall summer conditions showing oxygen levels supportive of healthy to moderately healthy infaunal habitat.

Overall, oxygen within the Harbor bottom waters appears to remain at ecologically healthy levels, except for periodic oxygen depletion within the deepest portions of the Quaise and Wauwinet basins. However, as there were some oxygen depletions below 5 mg L-1 in the main basins (although infrequent), it appears that the system is at or just beyond it ability to assimilate additional nitrogen/organic matter. Increasing organic matter deposition either through direct inputs or via enhanced production from increased nutrient loading is nearly certain to increase the level of oxygen related ecological stress. Decreasing organic matter deposition, either through lowered production or increased export should result in improvements in benthic habitat within these basins.

Infaunal Communities: The infaunal data (MEP and Harbor Study surveys) indicated an overall system supporting generally healthy infaunal habitat relative to the ecosystem types represented. Evaluation of infaunal habitat quality considered the natural structure of each system relative to the type of infaunal communities that they support.

The infaunal data clearly show that the lower basins and shallower areas (<12') of the main Harbor basins generally support high quality infaunal habitat. The lowermost basin (Town) exhibited a dense, highly diverse and relatively evenly distributed community, with some variation. The shallower margins of both Quaise and Head of the Harbor were only slightly less diverse than areas nearer the tidal inlet, but were clearly of high quality. This is further evidenced by the growth of epibenthic scallops in these areas. Within the main Harbor basins, only the deep "holes" showed reduced numbers of species and individuals and organic enrichment indicators. This indication of moderate to poor habitat in these deep regions is consistent with the previous analysis and supported by the observed accumulations of organic detritus in these natural depositional areas. It is unlikely that management of nitrogen loading will be able to create significant improvement within these deep basin regions and it is likely that these areas have been "stressed" by natural processes for a long time.

Both the MEP and Harbor Study surveys found Polpis Harbor to be supportive of both moderate to large numbers of species and individuals of diverse and even distribution. However, both studies found the habitat in both the east and west basins to be dominated by productive communities dominated by organic matter enrichment indicators, presently *Mediomastus*. It is likely that this community is structured by the enclosed nature of Polpis Harbor and its associated wetland, which results in enrichment of nitrogen and organic matter and deposition to the sediments. However, the benthic community is clearly productive and diverse and therefore, for its local environment appears healthy.

Overall, the MEP system-wide survey found higher numbers of species and individuals in communities that were generally more diverse and evenly distributed than the other 20 embayments examined to day by the MEP in southeastern Massachusetts. This is consistent with the relatively low tidally averaged nitrogen levels within the system, <0.40 mg N L-1 and generally 0.285-0.361 mg N L^{-1}. It should be noted that this upper limit of the Nantucket Harbor System tidally averaged nitrogen level compares well to the levels found to support healthy infauna in West Falmouth Harbor (main basin) of 0.38 mg N L^{-1}, the Phinneys Harbor System of <0.42 mg N L^{-1} and in enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg N L^{-1} were found to be supportive of healthy infaunal habitat. It appears that the primary habitat concern for the Nantucket Harbor System is the present decline in eelgrass coverage.

VIII.2. THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout an embayment system, is to first identify a sentinel location within the embayment and second to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality. The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined, the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved.

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Nantucket Harbor Estuarine System is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. Given the database it is possible to develop a site-specific threshold, which is a refinement upon general threshold analysis frequently employed.

The Nantucket Harbor System is presently supportive of infaunal habitat throughout its main basins, but is clearly impaired by nitrogen enrichment within the Head of the Harbor basin and in the eastern basin of Polpis Harbor, based upon eelgrass losses.. Given the documented importance of eelgrass habitat to these basins and the demonstrable loss of eelgrass that were supported, eelgrass restoration in these basins was set as the primary nitrogen management goal for the overall System. Due to the semi-isolated nature of Polpis Harbor from Nantucket Harbor, it is necessary to establish 2 sentinel stations for eelgrass, one in the Head of the Harbor and one in the east basin of Polpis Harbor (e.g. where eelgrass had been observed in 1951-1989).

Infaunal habitat is also important within the Nantucket Harbor System. However, under present nitrogen loading and watercolumn levels, infaunal habitats are generally healthy, with the exception of the deep regions of the deep basins, which are structurally "impaired". The System supports generally higher numbers of species and individuals in communities that are generally more diverse and evenly distributed than the other 20 embayments examined to date by the MEP in southeastern Massachusetts. These healthy infaunal habitats are consistent with the relatively low tidally averaged nitrogen levels throughout the Nantucket Harbor System, <0.40 mg N L-1 and generally 0.285-0.361 mg N L^{-1}. It should be noted that this upper limit of the Nantucket Harbor System tidally averaged nitrogen level, compares well to the levels found to support healthy infauna in West Falmouth Harbor (main basin) of 0.38 mg N L^{-1}, the Phinneys Harbor System of <0.42 mg N L^{-1} and in enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg N L^{-1} were found to be supportive of healthy infaunal habitat. Therefore no secondary infaunal planning nitrogen thresholds were developed for this estuary.

The tidally averaged total nitrogen threshold to support eelgrass at documented historical levels throughout the Nantucket Harbor System are based upon the water quality monitoring and modeling data and the observed temporal and spatial changes in eelgrass distribution within Head of the Harbor and Polpis Harbor east basin. In addition, evaluation of the nitrogen loading under present conditions and with no anthropogenic watershed inputs (Section VI) provides insight into the temporal effects of watershed nitrogen loading versus the much larger atmospheric source to this estuary.

It is important to note that the nitrogen levels throughout the Nantucket Harbor System remain relatively low, consistent with the oxygen conditions, lack of macroalgae and chlorophyll a levels. However, the water depth of the Harbor and possibly vertical and horizontal mixing rates appear to have resulted in a decline in eelgrass bed coverage from the deeper areas and more enclosed basin areas. While eelgrass was only recently lost from the east basin of Polpis Harbor, it is presently absent at a tidally average total nitrogen (TN) level of 0.361 mg N L-1. Loss at this nitrogen level is consistent with observed losses in West Falmouth Harbor above 0.350 mg N L-1, however, given the shallower depth of Polpis Harbor, it is likely that it is just slightly above its threshold level at present. Similarly, tidally averaged levels in the lower reach of Head of the Harbor (0.340-0.353) and mid and upper reach (0.390 mg N L-1) also suggest that the recent bed losses are from a recent exceedance of the supportive nitrogen threshold. Given all of the factors discussed above and the similarity of Head of the Harbor to conditions in West Falmouth and Phinneys Harbors and its present nitrogen levels, a nitrogen threshold of 0.350 mg N L-1 was determined to be supportive of eelgrass habitat in this system. This threshold should also support eelgrass in the shallower regions as well. As the east basin of

Polpis Harbor has only recently lost its eelgrass and is presently 0.361 mg N L-1, but has shallower waters than Head of the Harbor, only a slight reduction over present levels appears to be needed to support eelgrass habitat. Clearly the threshold must be lower than the present 0.361 mg N L^{-1} and higher than that for Head of the Harbor (0.350 mg N L^{-1}). Therefore, a threshold of 0.355 mg N L-1 was set for the sentinel station in Polpis Harbor. It should be noted that the Polpis Harbor threshold is well constrained by the available data, but is at the limits of the sensitivity of the MEP approach. Therefore concerning eelgrass, management should focus on no net increase in nitrogen loading to the Harbor System and as possible some reduction over current loading levels to Polpis Harbor and Head of the Harbor basins. The nitrogen loads associated with the threshold concentration at the sentinel location are discussed in Section VIII.3, below.

VIII.3 DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Nantucket Harbor system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Because the Harbor system is just slightly over the threshold, and because extensive sewering is already in place in the Town watershed, two threshold scenarios where modeled in order to demonstrate the level of effort required to achieve the threshold concentrations set for this system at the 2 sentinel stations for eelgrass in the Head of the Harbor and Polpis Harbor (east basin). Two sentinel stations are needed for this System due to the semi-isolated nature of Polpis Harbor from Nantucket Harbor. A comparison between present septic and total watershed loading and the loadings for the two modeled threshold scenarios is provided in Tables VIII-2 and VIII-3.

The first threshold scenario (scenario “A”) considers the water quality improvements that are possible with 100% of the present septic watershed load from the town watershed, and also 80% removal of the total anthropogenic watershed loads (septic, fertilizer and non-pervious surfaces) from the remaining three Harbor watersheds. The intent of this scenario is to simulate the likely loading condition of the Harbor approximately 50 years before present, at a time when eelgrass is documented to have existed in Polpis Harbor.

The second threshold scenario (scenario “B”) considers water quality improvements that are possible with the removal of 100% of septic loads from all four of the Harbor Watersheds. Though this is not a likely solution, this scenario does indicate the maximum possible benefit from septic removal alone.

These scenarios represent only two of a suite of potential reduction approaches that need to be evaluated by the community. The model results of these scenarios aid in establishing the general degree and spatial pattern of reduction that is possible toward the goal of restoration of this system. The modeling results provide one manner of achieving the selected threshold level for the sentinel sites within the estuarine system; these specific examples do not represent the only method for achieving this goal. However, the thresholds analysis provides general guidelines needed for the nitrogen management of this embayment.

Tables VIII-4 and VIII-5 show the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Tables VIII-4 and VIII-5, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent ‘worst-case’ summertime conditions. The benthic flux for these scenarios is reduced from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Nantucket Sound, as discussed in Section VI.

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the Nantucket Harbor system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.

sub-embayment	present septic load (kg/day)	threshold "A" septic load (kg/day)	Threshold "A" septic load % change	threshold "B" septic load (kg/day)	Threshold "B" septic load % change
Head of the Harbor	0.705	0.141	-80.0%	0.000	-100.0%
Polpis Harbor	0.435	0.087	-80.0%	0.000	-100.0%
Quaise Basin	0.392	0.078	-80.0%	0.000	-100.0%
Town Basin	5.194	0.000	-100.0%	0.000	-100.0%
System Total	6.726	0.306	-95.4%	0.000	-100.0%

Table VIII-3. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Nantucket Harbor system. 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 "A" load (kg/day)	threshold "A" % change	threshold "B" load (kg/day)	threshold "B" % change
Head of the Harbor	1.858	0.792	-57.4%	1.153	-37.9%
Polpis Harbor	3.529	2.175	-38.4%	3.093	-12.3%
Quaise Basin	2.123	1.140	-46.3%	1.732	-18.5%
Town Basin	15.901	10.707	-32.7%	10.707	-32.7%
System Total	23.411	14.814	-36.7%	16.685	-28.7%

Table VIII-4. Threshold "A" sub-embayment loads used for total nitrogen modeling of the Nantucket Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Head of the Harbor	0.792	22.239	-16.795
Polpis Harbor	2.175	2.190	26.450
Quaise Basin	1.140	20.126	43.010
Town Basin	10.707	13.888	-2.892
System Total	14.814	58.443	49.772

Table VIII-5. Threshold "B" sub-embayment loads used for total nitrogen modeling of the Nantucket Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux			
sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Head of the Harbor	1.153	22.239	-17.182
Polpis Harbor	3.093	2.190	26.655
Quaise Basin	1.732	20.126	42.885
Town Basin	10.707	13.888	-2.892
System Total	16.685	58.443	49.466

Modeled TN concentrations for present loading conditions and the two modeled scenarios are presented in Table VIII-6. Contour plots of model output for the two separate scenarios are show in Figures VIII-1 and VIII-2. The model results show that because N loading to the Nantucket Harbor system is dominated by atmospheric deposition and benthic flux, large percentage reductions in the anthropogenic N sources to the Harbor result only in small changes to TN concentrations in the system. For example, a -36.7% reduction in the total system watershed load in scenario "A" results in only a -1.5% reduction in TN concentrations at the sentinel station in East Polpis Harbor. These small changes in TN are necessary to re-establish eelgrass habitat in areas where it was found circa 1950.

Table VIII-6. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the Nantucket Harbor system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The threshold stations are shown in bold print (Sta. 2.1 is SMAST 2A, Sta. 4 is Town 6 and SMAST 4, see Table VI-1).						
Sub-Embayment	monitoring station	present (mg/L)	threshold "A" (mg/L)	threshold "A" % change	Threshold "B" (mg/L)	threshold "B" % change
Head of the Harbor - Upper	2	0.397	0.392	-1.3%	0.393	-1.0%
Head of the Harbor - Mid	2.2	0.390	0.385	-1.3%	0.386	-1.0%
Head of the Harbor - Lower	**2.1**	**0.353**	**0.349**	**-1.1%**	**0.350**	**-0.8%**
Pocomo Head	3	0.340	0.336	-1.0%	0.337	-0.8%
Quaise Basin	3.1	0.325	0.322	-0.9%	0.323	-0.7%
East Polpis Harbor	**4**	**0.361**	**0.356**	**-1.5%**	**0.358**	**-1.0%**
West Polpis Harbor	4.1	0.371	0.365	-1.6%	0.367	-1.0%
Abrams Point	5	0.296	0.294	-0.5%	0.295	-0.4%
Monomoy	6	0.291	0.289	-0.7%	0.289	-0.7%
Mooring Area	7	0.285	0.284	-0.4%	0.284	-0.4%

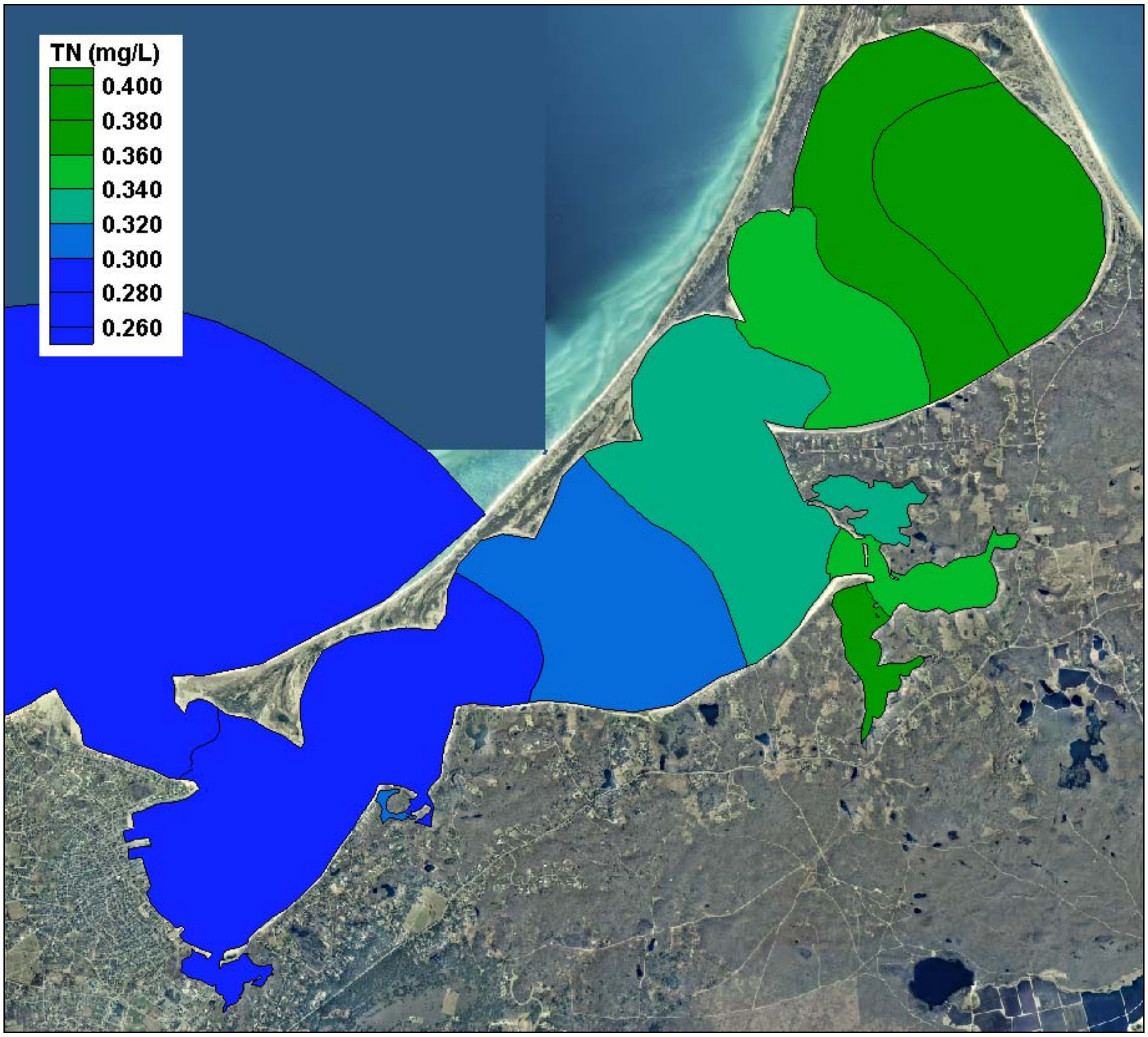


Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Nantucket Harbor system, for threshold "A" loading conditions.

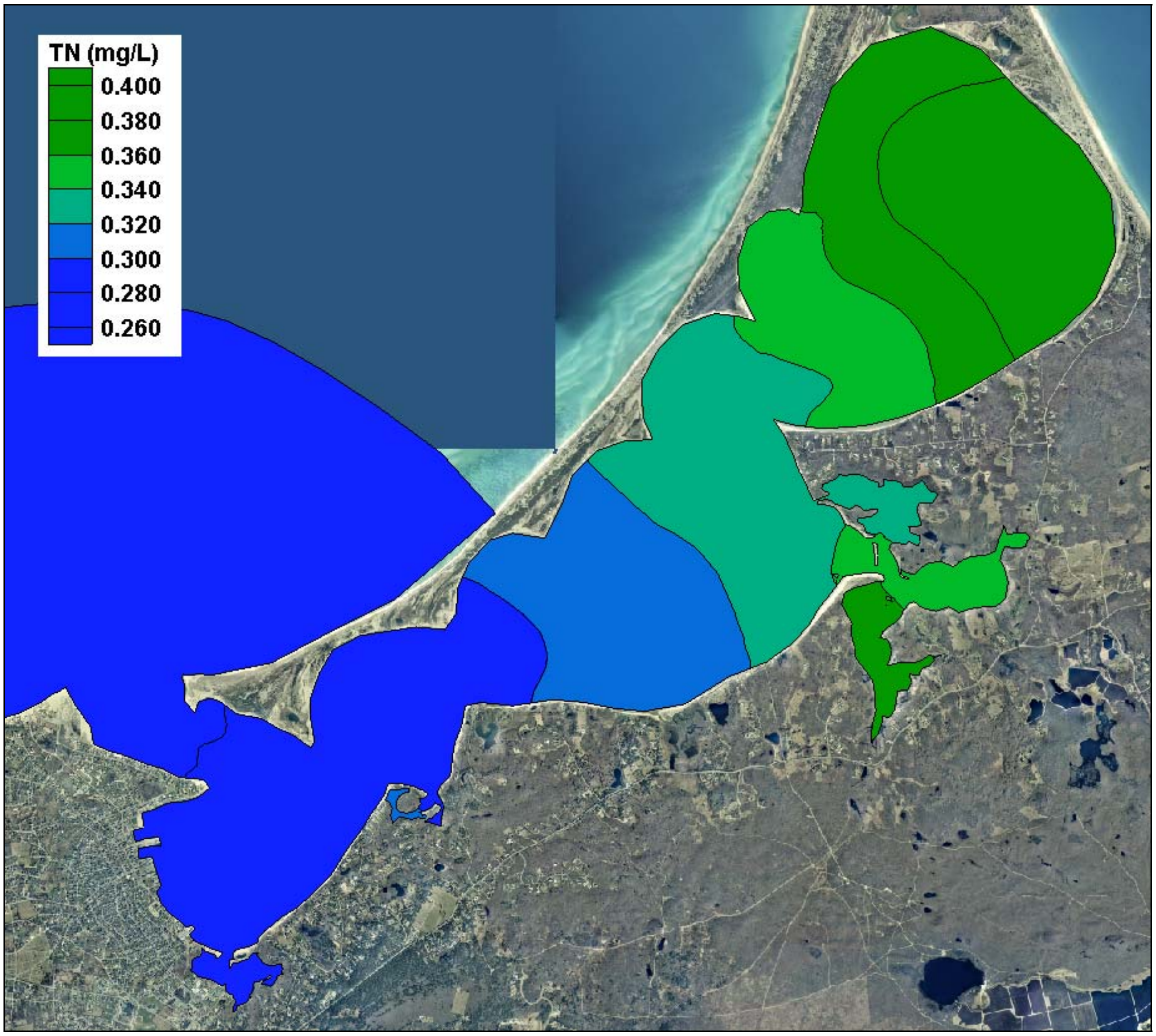


Figure VIII-2. Contour plot of modeled total nitrogen concentrations (mg/L) in the Nantucket Harbor system, for threshold "B" loading conditions.

IX. REFERENCES

Andrews, J.C. 1944. Map of Nantucket Harbor showing eelgrass colonies in the 1940's. Town of Nantucket Report.

Applied Science Associates (C. Swanson and M Ward). 2000. Computer Modeling of Nantucket Harbor: Project Summary. Final Report to the Town of Nantucket.

Brawley, J.W., G. Collins, J.N. Kremer, C.-H. Sham, and I. Valiela. 2000. A time-dependent model of nitrogen loading to estuaries form coastal watersheds. Journal of Environmental Quality 29:1448-1461.

Brigham Young University (1998). "User's Manual, Surfacewater Modeling System."

BUMP Study (I Valiela, M Cole, and J York). 2000. Land-derived nitrogen loading to Nantucket Harbor. Boston University Marine Program, Draft Final Report to Applied Science Associates

Burns, K., M. Ehrhardt, B. Howes and C. Taylor., 1993. Subtidal benthic community respiration and production rates near the heavily oiled coast of Saudi Arabia. Marine Pollution Bull. 27:199-205.

Cambareri, T.C. and E.M. Eichner. 1998. Watershed Delineation and Ground Water Discharge to a Coastal Embayment. *Ground Water*. 36(4): 626-634.

Cape Cod Commission, (1998). "Cape Cod Coastal Embayment Project." Barnstable, MA.

Cape Cod Commission Water Resources Office, 1991. Technical Bulletin 91-001, Nitrogen Loading.

Cape Cod Commission Water Resources Office, 1998. Cape Cod Coastal Embayment Project Interim Final Report.

Cape Cod Commission. 1996. "Monomoy Capacity Study, Summary Report".

Cape Cod Commission. 2000. "Coastal Nitrogen Loading Project".

Cape Cod Commission. 1993. "Monomoy Lens Groundwater Protection Project"

CDM and Howes, B.L., 2000 Water Quality Evaluation of the Wareham River Estuary Complex. Final Report to the Town of Wareham. Camp, Dresser and McKee Inc. 300pp.

Costa, J.E., B.L. Howes, I. Valiela and A.E. Giblin. 1992. Monitoring nitrogen and indicators of nitrogen loading to support management action in Buzzards Bay. In: McKenzie et al. (eds.) Ecological Indicators, Chapt. 6, pp. 497-529.

Costa, J.E., G. Heufelder, S. Foss, N.P. Millham, B.L. Howes. 2002. Nitrogen Removal Efficiencies of Three Alternative Septic System Technologies and a Conventional Septic System. Environment Cape Cod 5(1): 15-24.

Creighton, C. 1988. Natural and Man-made Resource Inventory of Nantucket and Madaket Harbors. Report to the Nantucket Land Council and Nantucket Harbor Planning Advisory Committee.

DeSimone, L.A. and B.L. Howes. 1996. Denitrification and nitrogen transport in a coastal aquifer receiving wastewater discharge. *Environmental Science and Technology* 30:1152-1162

D'Elia, C.F, P.A. Steudler and N. Corwin. 1977. Determination of total nitrogen in aqueous samples using persulfate digestion. Limnology and Oceanography 22:760-764.

Draft Environmental Impact Report, Analysis of Pond Management Alternatives, Sesachacha Pond, Nantucket, July 1989. Aubrey Consulting Incorporated. EOEA File Number 7452

Dyer, K.R. (1997). Estuaries, A Physical Introduction, 2nd Edition, John Wiley & Sons, NY, 195 pp.

Eichner, E.M. and T.C. Cambareri. 1992. Technical Bulletin 91-001: Nitrogen Loading. Cape Cod Commission, Water Resources Office, Barnstable, MA. Available at: http://www.capecodcommission.org/regulatory/NitrogenLoadTechbulletin.pdf

Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas. Cape Cod Commission. Barnstable, MA.

Eichner, E.M., T.C. Cambareri, K. Livingston, C. Lawrence, B. Smith, and G. Prahm. 1998. Cape Coastal Embayment Project: Interim Final Report. Cape Cod Commission, Barnstable, MA.

Fischer, H. B., List, J. E., Koh, R. C. Y., Imberger, J., and Brooks, N. H. (1979). *Mixing in inland and coastal waters*. Academic. San Diego.

Frimpter, M.H., J.J. Donohue, M.V. Rapacz. 1990. A mass-balance nitrate model for predicting the effects of land use on groundwater quality. U.S. Geological Survey Open File Report 88:493.

Gardner, K.K. and R.M. Vogel. 2005. Predicting Ground Water Nitrate Concentration from Land Use. *Ground Water*, 43(3): 343-352.

Henderson, F. M. (1966). *Open Channel Flow*. Macmillan Publishing Company, New York. pp. 96-101.

Horsley, Witten Hegemann, Inc. Nantucket water Resources Management Plan, 1990. Prepared for the Nantucket Land Council.

Howes, B.L. and D.D. Goehringer. 1989. Preliminary water quality survey, Nantucket Harbor to Wauwinet Harbor. Woods Hole Oceanographic Institution Report to the Town of Nantucket, pp. 18.

Howes, B.L. and C.T. Taylor., 1990 Nutrient Regime of New Bedford Outer Harbor: Infaunal Community Structure and the Significance of Sediment Nutrient Regeneration to Water

Column Nutrient Loading. Final Technical Report to Camp, Dresser and McKee, Boston, Mass. for the City of New Bedford, Mass. and EPA. 140 pp.

Howes, B.L. and D.D. Goehringer. 1994. Nutrient status of the coastal salt ponds of Falmouth, Ma: Report of the Pondwatch Program.

Howes BL. 1998. Sediment metabolism within Massachusetts Bay and Boston Harbor relating to rates and controls of sediment-water column exchanges of nutrients and oxygen in 1997. Boston: Massachusetts Water Resources Authority. Report 1998-20. 80 p

Howes, B.L. and D.D. Goehringer. 1996. The Ecology of Buzzards Bay: An Estuarine Profile. USFWS Community Profile Series Biological Report 31.

Howes, B.L. and D.D. Goehringer. 1997. Falmouth's Coastal Salt Ponds. Falmouth Pondwatch Program, 1987-1996.

Howes, B.L., R.I. Samimy, B. Dudley, 2003, Site Specific Nitrogen Thresholds for Southeastern Massachusetts Embayments: Critical Indicators Interim Report, Massachusetts Estuaries Project for the Massachusetts Department of Environmental Protection.

Howes, B.L., J.S. Ramsey and S.W. Kelley, 2001. Nitrogen modeling to support watershed management: comparison of approaches and sensitivity analysis. Final Report to MA Department of Environmental Protection and USEPA, 94 pp. Published by MADEP.

Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2003). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Stage Harbor, Sulphur Springs, Taylors Pond, Bassing Harbor and Muddy Creek, Chatham, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, J. Wood, E. Eichner (2004). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Popponesset Bay, Mashpee and Barnstable, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B.L., J. Ramsey, E.M. Eichner, R.I. Samimy, S. W. Kelley, D.R. Schlezinger (2005). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Oyster Pond System, Falmouth, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B., Trey Ruthven, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2005). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Rushy Marsh Pond, Barnstable, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA

Jaworski, N.A. 1984. Sources of nutrients and the scale of eutrophication problems in estuaries. In: Estuaries and Nutrients; B.J. Neilson and L.E. Cronin (Eds.); Humana Press: Clifton, N.J., pp. 83-110.

Jaworski, N.A., P.M. Groffman, A.A. Keller, J.C. Prager. 1992. Estuaries **15**:83-95.

Jorgensen, B.B. 1977. The sulfur cycle of a coastal marine sediment (Limfjorden, Denmark). Limnology Oceanography, 22:814-832.

Kelley, K.M. 1982. Eelgrass distribution on Nantucket. Town of Nantucket Health Department Report.

Kelley, K.M. 1985. An update on the management of the Nantucket Bay scallop resource. Nantucket Marine Department.

Kelley, K.M. 1989. Distribution of Eelgrass in Nantucket Harbor, MA., Summer 1989. Town of Nantucket Health Department, Report, 12pp.

King, Ian P. (1990). "Program Documentation - RMA2 - A Two Dimensional Finite Element Model for Flow in Estuaries and Streams." Resource Management Associates, Lafayette, CA.

Klump, J. and C. Martens. 1983. Benthic nitrogen regeneration. In: Nitrogen in the Marine Environment, (Carpenter & Capone, eds.). Academic Press.

Knott, J.F. and J.C. Olimpio. 1986. Estimation of Recharge Rates to the Sand and Gravel Aquifer Using Environmental Tritium, Nantucket Island, Massachusetts. US Geological Survey. Water Supply Paper 2297

Koppelman, L.E. (Ed.). 1978. The Long Island comprehensive waste treatment management plan. Vol II. Summary documentation report, Long Island Regional Planning Board, Hauppage, N.Y.

L. Lidz 1965. Sedimentary environment and foraminiferal parameters: Nantucket Bay, Massachusetts, Limnology and Oceanography 10:392-402

Lindeburg, Michael R. (1992). *Civil Engineering Reference Manual, Sixth Edition*. Professional Publications, Inc., Belmont, CA.

Lurbano, L.D. October, 2001. The Impact of Climatic Change on Ground Water Systems. Thesis submitted for partial fulfillment of requirements for Ph.D. at the University of Minnesota. M. Person, Advisor. (listed at http://des.memphis.edu/lurbano/thesis/thesis.html#thesisli2.html)

Massachusetts Department of Environmental Protection. 1999. DEP Nitrogen Loading Computer Model Guidance. Bureau of Resource Protection. Boston, MA. Available at: http://www.state.ma.us/dep/brp/dws/techtool.htm

Massachusetts Department of Revenue. November, 2002. Property Type Classification Codes.

Malone, T.C. 1992. Effects of Watercolumn Processes on Dissolved Oxygen, Nutrients, Phytoplankton and Zooplankton. In: Oxygen Dynamics in the Chesapeake Bay: A Synthesis of Research; D.E. Smith, M. Leffler and G. Mackiernan (Eds.); Maryland Sea Grant College Publishers, pp. 61-112.

Michael T. Hoover, Ph.D. 1997. A Framework for Site Evaluation, Design, and Engineering of On-Site Technologies Within a Management Context".

Millham, N. and B.L. Howes, 1990. Surfacewater Nutrient Flux from the Mill Brook Watershed: Cranberry Bogs, Freshwater Marshes and Nutrient Inputs to the Nantucket/Polpis Harbor System, Appendix I of the Nantucket Harbor Study Final Report.

Millham, N. and B.L. Howes, 1993. Nutrient balance of a shallow coastal embayment: I. Patterns of groundwater discharge. Marine Ecology Progress Series **112**: 155-167.

Millham, N.P. and B.L. Howes, (1994a). Freshwater flow into a coastal embayment: groundwater and surface water inputs. Limnology and Oceanography 39: 1928-1944.

Millham, N.P. and B.L. Howes (1994b). Patterns of groundwater discharge to a shallow coastal embayment. Marine Ecology Progress Series 112:155-167.

Murphy, J. and J.P. Reilly, 1962. A Modified Single Solution Method for the Determination of Phosphate in Natural Waters. Analytica Chemica Acta, v. 27, p. 31-36

Nantucket Harbor Watershed Work Group Report. 2003

Nelson, M.E., S.W. Horsley, T.C. Cambareri, M.D. Giggey and J.R. Pinnette. 1998. Predicting nitrogen concentrations in groundwater- An analytical model. Focus Conference on Eastern Groundwater Issues, National Water Well Association, Stamford, CT.

Norton, W.R., I.P. King and G.T. Orlob (1973). "A Finite Element Model for Lower Granite Reservoir", prepared for the Walla Walla District, U.S. Army Corps of Engineers, Walla Walla, WA.

Oldale R. and R.N. Barlow, 1984. Geologic Map of Cape Cod and the Islands. Miscellaneous Investigations Series. U.S. Geological Survey Map I-1763.

Oldale, R. and O'Hara, 1980. New radiocarbon dates from the inner continental shelf of southeastern Massachusetts and a local sea-level-rise curve for the past 12,000 yr. Geology **8**: 61-74.

Olinger, S.V., J.D. Aber, G.M. Lovett, S.V. Millham, R.G. Lathrop, J.M. Ellis, 1993. A spatial model of atmospheric deposition for the northeastern U.S. Ecological Applications **3**: 459-472.

Ramsey, J.S., B.L. Howes, S.W. Kelley, and F. Li (2000). “Water Quality Analysis and Implications of Future Nitrogen Loading Management for Great, Green, and Bournes Ponds, Falmouth, Massachusetts.” Environment Cape Cod, Volume 3, Number 1. Barnstable County, Barnstable, MA. pp. 1-20.

Ramsey, John S., Jon D. Wood, and Sean W. Kelley, (1999). “Two Dimensional Hydrodynamic Modeling of Great, Green, and Bournes Ponds, Falmouth, MA.” Applied Coastal Research and Engineering, Inc. report prepared for the Town of Falmouth and Horsley & Witten, Inc. 41 pp.

Ramsey, J.S., B.L. Howes, N.P. Millham, and D. Bourne. 1995. Hydrodynamic and water quality study of West Falmouth Harbor, Falmouth MA. Aubrey Consulting Inc. Technical Report for Town of Falmouth, pp. 81.

Redfield, A.C. and M. Rubin. 1962. The age of salt marsh peat and its relation to recent changes in sea level at Barnstable, Massachusetts. Proceedings of the National Academy of Sciences 48:1728-1735.

Rhoads, D.C. and J.D. Germano. 1986. Interpreting long-term changes in benthic community structure: a new protocol. Hydrobiologia 142:291-308

Robertson, W.D., J.D. Cherry, and E.A. Sudicky. 1991. ³Ground-Water Contamination from Two Small Septic Systems on Sand Aquifers.² Ground Water. 29(1): 82-92.

Rosen, P. 1976. Origin and Processes of Cuspate Spit Shorelines. Estuarine Research **II**: 77-92.

Ryther, J.H., and W.M. Dunstan. 1971. Nitrogen, phosphorous and eutrophication in the coastal marine environment. Science, 171:1008-1012.

Scheiner, D. 1976. Determination of ammonia and Kjeldahl nitrogen by indophenol method. Water Resources 10: 31-36.

Shepard, F.C. Waquoit Bay National Estuarine Research Reserve. 1996. "Managing Wastewater: Prospects in Massachusetts for a Decentralized Approach".

Shepard, F.C. Waquoit Bay National Estuarine Research Reserve. 1996. "A Massachusetts Guide to Needs Assessment and Evaluation of Decentralized Wastewater Treatment Alternatives".

Smith, K.N. and B.L. Howes, 2006. Attenuation of watershed nitrogen by a small New England salt marsh. Manuscript in review

Smith, R.L., B.L. Howes and J.H. Duff. 1991. Denitrification in nitrate-contaminated groundwater: occurrence in steep vertical geochemical gradients. Geochimica Cosmochimica Acta 55:1815-1825.

Taylor, C.D. and B.L. Howes, 1994. Effect of sampling frequency on measurements of seasonal primary production and oxygen status in near-shore coastal ecosystems. Marine Ecology Progress Series 108: 193-203.

US Army, Engineer Research and Development Center, Waterways Experiment Station, Coastal and Hydraulics Laboratory, Users Guide To RMA4 WES Version 4.5, June 05, 2001.

USGS web site for groundwater data for Massachusetts and Rhode Island: http://ma.water.usgs.gov/ground_water/ground-water_data.htm

Vanek, V. 1993. Groundwater regime of a tidally influenced coastal pond. J. Hydrology **151**: 317-342.

Van de Kreeke, J. (1988). “Chapter 3: Dispersion in Shallow Estuaries.” In: Hydrodynamics of Estuaries, Volume I, Estuarine Physics, (B.J. Kjerfve, ed.). CRC Press, Inc. pp. 27-39.

Walter, D.A., A. Whealan (2004). Simulated Water Sources and Effects of Pumping on Surface and Ground Water, Sagamore and Monomoy Flow Lenses, Cape Cod, Massachusetts. USGS Scientific Investigations Report 2004-5181

Weiskel, P.K. and B.L. Howes. 1991. Dissolved nitrogen flux through a small coastal watershed. Water Resources Research **27**: 2929-2939.

Weiskel, P.K. and B.L. Howes. 1992. Differential transport of nitrogen and phosphorus from septic systems through a coastal watershed. Environmental Science and Technology **26**: 352-360.

WHOI Nantucket Harbor Study (B.L. Howes, D.D. Goehringer, N.P. Millham, D.R. Schlezinger, G.R. Hampson, C.D. Taylor and D.G. Aubrey). 1997. Nantucket Harbor Study: A quantitative assessment of the environmental health of Nantucket Harbor for the development of a nutrient management plan. Woods Hole Oceanographic Institution Final Report to the Town of Nantucket, 140 pp.

Wood, J.D., J.S. Ramsey, and S. W. Kelley, (1999). "Two-Dimensional Hydrodynamic Modeling of Barnstable Harbor and Great Marsh, Barnstable, MA." Applied Coastal Research and Engineering, Inc. report prepared for the Town of Barnstable. 28 pp.

Zimmerman, J.T.F. (1988). "Chapter 6: Estuarine Residence Times." In: Hydrodynamics of Estuaries, Volume I, Estuarine Physics, (B.J. Kjerfve, ed.). CRC Press, Inc. pp. 75-84.