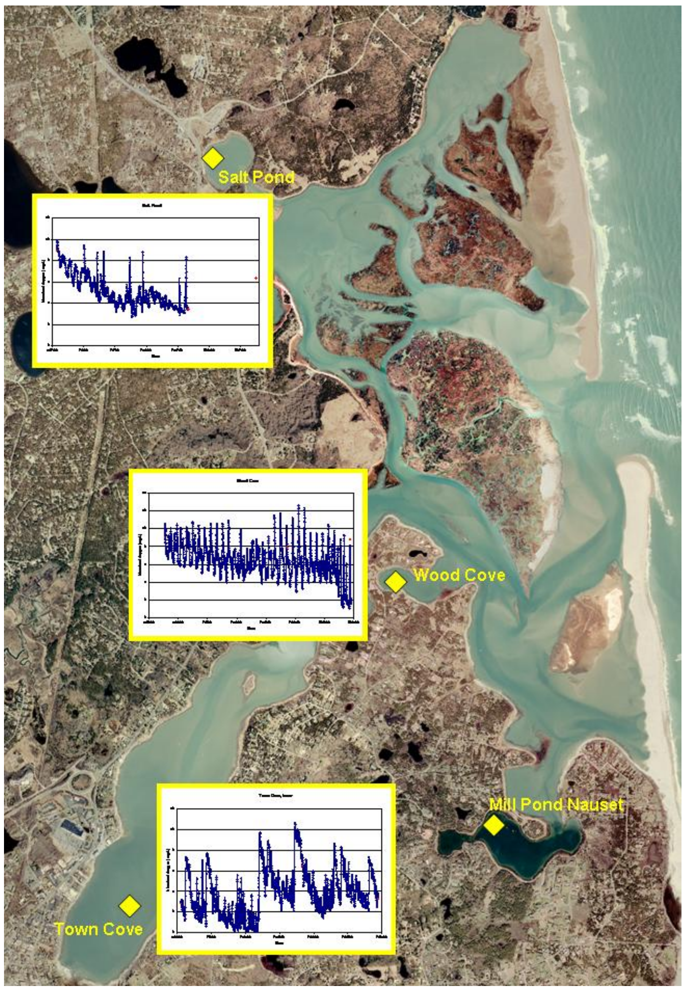
Massachusetts Estuaries Project

Linked Watershed-Embayment Approach to Determine Critical Nitrogen Loading Thresholds for the Nauset Harbor Embayment System Towns of Orleans and Eastham, Massachusetts



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Massachusetts Department of
Environmental Protection

FINAL REPORT – December 2012

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Linked Watershed-Embayment Approach to Determine Critical Nitrogen Loading Thresholds for the Nauset Harbor Embayment System Towns of Orleans and Eastham, Massachusetts

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Executive Summary

1. Background

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Nauset Harbor embayment system, a coastal embayment situated within the Town of Orleans and Eastham, Massachusetts. Analyses of the Nauset Marsh embayment system was performed to assist the Towns with up-coming nitrogen management decisions associated with current and future wastewater planning efforts, as well as wetland restoration, anadromous fish runs, shell fishery, and open-space programs. As part of the MEP approach, habitat assessment was conducted on the embayment based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure.

Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Town of Orleans and Eastham 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 Nauset 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 Towns) for the restoration / protection of the Nauset 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 Nauset Harbor embayment system within the Towns of Orleans and Eastham (though primarily a large salt marsh environment) is at risk of eutrophication (over enrichment) in its upper reaches (particularly Town Cove) if enhanced nitrogen loads entering through groundwater and surface water from the increasingly developed watersheds to this complicated estuarine system eventually exceed the ability of the salt marsh and embayment basins to uptake the nutrient loads. 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 Town of Orleans and Eastham have recognized the severity of the problem of eutrophication and the need for watershed nutrient management. Concern over declining resource quality of the estuarine systems of Orleans (inclusive of Namskaket Marsh, Little Namskaket Marsh, Rock Harbor and Pleasant Bay) prompted the Town of Orleans to initiate the town-wide Orleans Water Quality Monitoring Program in 2001, which continues in a reduced form through present (2012). The 2001 Program was an expansion of a previous effort targeting Pleasant Bay, begun in 1997 by the Orleans Water Quality Task Force. The town-wide monitoring program is focused on restoring and protecting the estuarine habitats associated with the Town of Orleans and is being undertaken in concert with the DEP/SMAST Massachusetts Estuaries Project. This is a collaborative effort whereby the Town of Orleans provides the support, coordination and oversight of the program through its Planning Office and through its Wastewater Management Steering Committee and SMAST provides the technical and analytical aspects needed for the project through the MEP Technical Team.

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

Nitrogen Loading Thresholds and Watershed Nitrogen Management: Realizing the need for scientifically defensible management tools has resulted in a focus on determining the aquatic system's assimilative capacity for nitrogen. The highest-level approach is to directly link the watershed nitrogen inputs with embayment hydrodynamics to produce water quality results that can be validated by water quality monitoring programs. This approach when linked to state-of-the-art habitat assessments yields accurate determination of the “allowable N concentration increase” or “threshold nitrogen concentration”. These determined nitrogen concentrations are then directly relatable to the watershed nitrogen loading, which also accounts for the spatial distribution of the nitrogen sources, not just the total load. As such, changes in nitrogen load from differing parts of the embayment watershed can be evaluated relative to the degree to which those load changes drive embayment water column nitrogen concentrations toward the “threshold” for the embayment system. To increase certainty, the “Linked” Model is independently calibrated and validated for each embayment.

Massachusetts Estuaries Project Approach: The Massachusetts Department of Environmental Protection (DEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool to communities throughout southeastern Massachusetts (the Linked Watershed-Embayment Management Model) for nutrient management in their coastal embayment systems. Ultimately, use of the Linked Watershed-Embayment Management Model tool by municipalities in the region results in effective screening of nitrogen reduction approaches and eventual restoration and protection of valuable coastal resources. The MEP provides technical guidance in support of policies on nitrogen loading to embayments, wastewater management decisions, and establishment of nitrogen Total Maximum Daily Loads (TMDLs). A TMDL represents the greatest amount of a pollutant that a waterbody can accept and still meet water quality standards for protecting public health and maintaining the designated beneficial uses of those waters for drinking, swimming, recreation and fishing. The MEP modeling approach assesses available options for meeting selected nitrogen goals that are protective of embayment health and achieve water quality standards.

The core of the Massachusetts Estuaries Project analytical method is the Linked Watershed-Embayment Management Modeling Approach, which links watershed inputs with embayment circulation and nitrogen characteristics.

The Linked Model builds on well-accepted basic watershed nitrogen loading approaches such as those used in the Buzzards Bay Project, the CCC models, and other relevant models. However, the Linked Model differs from other nitrogen management models in that it:

- requires site-specific measurements within each watershed and embayment;
- uses realistic “best-estimates” of nitrogen loads from each land-use (as opposed to loads with built-in “safety factors” like Title 5 design loads);
- spatially distributes the watershed nitrogen loading to the embayment;
- accounts for nitrogen attenuation during transport to the embayment;
- includes a 2D or 3D embayment circulation model depending on embayment structure;
- accounts for basin structure, tidal variations, and dispersion within the embayment;
- includes nitrogen regenerated within the embayment;
- is validated by both independent hydrodynamic, nitrogen concentration, and ecological data;
- is calibrated and validated with field data prior to generation of “what if” scenarios.

The Linked Model Approach’s greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing “what if” scenarios for evaluating watershed nitrogen management options.

For a comprehensive description of the Linked Model, please refer to the *Full Report: Nitrogen Modeling to Support Watershed Management: Comparison of Approaches and Sensitivity Analysis*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm. A more basic discussion of the Linked Model is also provided in Appendix F of the *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm. The Linked Model suggests which management solutions will adequately protect or restore embayment water quality by enabling towns to test specific management scenarios and weigh the resulting water quality impact against the cost of that approach. In addition to the management scenarios modeled for this report, the Linked Model can be used to evaluate additional management scenarios and may be updated to reflect future changes in land-use within an embayment watershed or changing embayment characteristics. In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries. Unlike many approaches, the Linked Model accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics and accommodates the spatial distribution of these processes. For an overview of several management scenarios that may be employed to restore embayment water quality, see *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm.

Application of MEP Approach: The Linked Model was applied to the Nauset Harbor embayment system by using site-specific data collected by the MEP and water quality data from the Orleans Water Quality Task Force Water Quality Monitoring Programs (see Chapter 2). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Planning Department in the Town of Orleans and Eastham and watershed boundaries were delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Nauset Harbor embayment system and associated sub-embayments (current and build-out loads are summarized in Chapter IV). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Nauset 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 bio-available and total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis while nitrogen entering the coastal embayment was quantified by direct measurement of stream nutrient concentrations and freshwater flow, predominantly groundwater, in the small stream discharging directly to the embayment. Boundary nutrient concentrations in the Atlantic Ocean source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Nauset 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 embayment.

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

The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout and embayment system, is to first identify a sentinel location within the embayment and second to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality (threshold nitrogen level). The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined, the Linked Watershed-Embayment Model is used to adjust nitrogen loads sequentially until the targeted nitrogen concentration is achieved. For the Nauset Harbor system, the restoration target should reflect both pre-degradation habitat quality and be reasonably achievable. The presentation in this report of nitrogen loading limits aims to establish the general degree and spatial pattern of loading that will be required for protection of this healthy salt marsh dominated embayment system.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen loading guidelines for future nitrogen management in the watershed to the Nauset Harbor embayment system. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in changes to nitrogen loading (increase or decrease) to the embayment. These scenarios should be developed in coordination with the Town of Orleans and Eastham in the Nauset Harbor watershed in order to effectively examine the effect of load increases/reductions on water column nutrient concentrations.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Nauset Harbor embayment system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. The Nauset Estuary is a complex estuary composed of 3 types of basins: tidal embayments (open water basins with little associated salt marsh) such as Town Cove, Salt Pond, Wood Cove, and Mill Pond; salt marsh ponds (salt marsh dominated open basins) such as Salt Pond Bay and Nauset Bay; and salt marsh tidal creeks with high tidal velocities and areas of shifting sands (tidal channels through emergent salt marsh) within Nauset Marsh. Each of these 3 basin types has different natural sensitivities to nitrogen enrichment and organic matter loading and each has its own benthic community indicative of an unimpaired or impaired habitat. The MEP evaluation of habitat quality considered the natural structure of each system and the types of infaunal communities and eelgrass coverages that they support under low and high levels of nitrogen enrichment. Currently, the Nauset Estuary is showing differences in nitrogen enrichment and habitat quality among its various component basins.

At present, eelgrass has nearly disappeared from the Nauset Estuary, with only a small area remaining adjacent Nauset Inlet. The observed loss is consistent with the level of nitrogen enrichment and tidal flows within this system and clearly indicates impairment of this resource. The overall pattern of eelgrass distribution and temporal decline in coverage is fully consistent with the spatial pattern of nitrogen enrichment (Section VI) and oxygen and chlorophyll levels in the various basins (Section VII). The pattern of decline is typical of environmental changes wrought by nutrient enrichment. Nutrient enrichment tends to result in loss of eelgrass habitat in the more tidally restricted basins (e.g. Town Cove), which also tend to be the focus areas for watershed nitrogen inputs. Salt Pond Bay exists along this nitrogen gradient, though less enriched than Town Cove. The pattern of loss from the tidal reaches furthest from the inlet can also be seen in the Nauset Harbor System, where the remaining eelgrass is adjacent the main inlet. This pattern parallels the gradient in nitrogen enrichment of these estuarine waters.

Overall, the infauna survey measured generally diverse and productive benthic animal communities throughout the salt marsh dominated basins and tidal creeks associated with Nauset Marsh and significantly impaired habitat within the nutrient enriched semi-enclosed basins, Town Cove, Salt Pond, Mill Pond and Wood Cove. Except for Wood Cove, these basins are relatively deep (>5m) and all exhibit periodic hypoxia and some anoxia of bottom waters during summer. Wood Cove and the small inner basin of Mill Pond have the additional benthic habitat impairment associated with dense accumulations of macroalgae, *Ulva*, a species associated with watershed nitrogen inputs in many Cape Cod estuaries. These 4 sub-basins currently support impaired benthic animal habitat.

3. Conclusions of the Analysis

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

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

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Nauset Harbor embayment system were comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally between 72% and 86% of the controllable watershed nitrogen load to the embayment was from wastewater.

Based upon the MEP analysis, eelgrass habitat was selected as the primary nitrogen management goal for the Nauset Estuary, specifically within Town Cove and Salt Pond Bay. Analysis of the 1951 and 2001 coverages indicates that an area of eelgrass habitat on the order of ~80 acres could be recovered if nitrogen management alternatives were implemented. In addition, it should be noted that the presence of the small region of eelgrass near Nauset Inlet should increase the rate of eelgrass recovery under reduced nitrogen loading by providing a source of seeds and propagules within the estuary. Given the greater sensitivity of eelgrass to nitrogen enrichment compared to infaunal habitat, restoring eelgrass should also result in mitigating nitrogen related impairment of benthic habitats, specifically, restoration of impaired infaunal habitat within each of the semi-enclosed basins (Town Cove, Salt Pond, Mill Pond, Wood Cove). While it is recognized that the deepest portions of Salt Pond and Mill Pond will likely continue to support impaired habitat due to the configuration of these basins and basin depth (>6 meters), impairment of the shallower adjacent areas should be secondary targets for restoration. With a reduction in nitrogen loading to Town Cove and Salt Pond Bay to restore eelgrass habitat, the benthic infaunal habitat throughout the Nauset Harbor Estuary would be restored with an increase in shellfish habitat and shift toward larger longer lived deep burrowing organisms.

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Nauset Harbor estuarine system is based primarily upon: 1) the systems structure and function as a salt marsh, 2) macroalgal distribution, 3) current benthic community indicators and 4) nitrogen levels. Given the database it is possible to develop a site-specific threshold, which is a refinement upon general threshold analysis frequently employed.

The Namskaket Estuary is presently supportive of high quality salt marsh infaunal habitat throughout its tidal reach. While there is periodic summertime oxygen depletion of creek waters, the levels are consistent with unimpaired New England salt marsh systems. At present, significant macroalgal accumulations do not occur within this macro-tidal estuary at tidally averaged total nitrogen levels of 0.662 mg N L-1 (headwaters) to 0.421 mg N L-1 (tidal inlet).

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

Nauset Harbor Threshold Nitrogen Concentrations

- The significant impairment of eelgrass habitat within Town Cove and Salt Pond Bay, as indicated by the complete loss of coverage associated with nitrogen enrichment makes the primary restoration target for the Nauset Estuary eelgrass restoration. At present, eelgrass has been virtually lost from the Nauset Estuary, with only a small bed remaining within the main creek to Nauset Inlet. The remaining eelgrass is associated with high nitrogen related water quality. While the remaining eelgrass within the Nauset Estuary is found at tidally averaged TN levels of 0.36 mg L^{-1}, this does not represent the nitrogen "threshold" level for eelgrass in this system. First, the site is generally deeper than the historic eelgrass areas in Town Cove and Salt Pond Bay, and therefore requires a lower nitrogen level to support eelgrass. Second, a threshold represents the level at which eelgrass is sustainable, but if nitrogen increases, eelgrass begins to decline. At present, we only know that this site is relatively stable, but not the required temporal analysis. The result is that that the nitrogen threshold for eelgrass in the inner basins cannot be lower than 0.36 mg L^{-1}.

- Synthesis of the available eelgrass and nitrogen data indicates that the threshold nitrogen level to support high quality stable eelgrass habitat within the historic coverage areas of the Nauset Estuary is >0.36 mg L^{-1} (level in the remaining bed) but <0.50 mg L^{-1}, since areas of eelgrass loss in the Nauset Estuary have levels >0.50 mg L^{-1}. Comparison to other systems indicates similar findings, but with high quality habitat at 0.45 mg L^{-1} (Bournes Pond, Parkers River), 0.43 mg L^{-1} (Westport River), but impaired habitat at TN levels of 0.48 mg L^{-1} (Bournes Pond), and 0.50 mg L^{-1} (Waquoit Bay, Westport River, Bass River).

- Based upon the above analysis a single sentinel station was selected at the long term monitoring station in Town Cove, WMO-27 (at the uppermost edge of the main historic bed), for the re-establishment of the expansive beds at this location and in the region between this station and outer impaired areas, as well as the fringing beds at the head of the Cove. This determination is directly linked to analysis of the historical eelgrass coverage. The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location was determined to be 0.45 mg TN L^{-1}, with a secondary check to lower the Salt Pond Bay TN level to <0.45 mg N L^{-1}. As there has not been significant eelgrass habitat within the Nauset Estuary for over a decade, this threshold was based upon analysis of remaining eelgrass beds and comparison to other local embayments of similar depths and structure under MEP analysis.

- Based upon these observations, the MEP Technical Team concluded that an upper limit of 0.50 mg N L^{-1} tidally averaged TN would support healthy infaunal habitat in the semi-enclosed embayment basins of the Nauset Estuary. This represent a secondary threshold as achieving the primary nitrogen threshold, 0.45 mg L^{-1}, to restore eelgrass in Town Cove and Salt Pond Bay, will likely lower nitrogen levels within the semi-enclosed, as well. It should be emphasized that these secondary criteria values were not used for setting the primary nitrogen threshold in this estuarine system. These secondary targets merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station within Town Cove.

It is important to note that the analysis of future nitrogen loading to the Nauset Harbor estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that significant increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. 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 Nauset Harbor estuarine system is that restoration will necessitate a reduction in the present (Orleans and Eastham land use/assessors data are from 2007, Brewster data are from 2004) 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 Nauset Harbor estuary system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. (mg/L)
SYSTEMS										
Nauset Marsh	1.022	2.528	8.201	--	10.729	11.252	46.838	68.819	0.42-0.58	--
Salt Pond	0.288	1.196	3.818	--	5.014	0.299	19.622	24.934	0.59	--
Woods Cove	0.038	0.142	0.603	--	0.745	0.241	4.657	5.643	0.51	--
Mill Pond	0.175	0.910	4.022	--	4.932	1.068	3.219	9.219	0.50-0.61	--
Rachel Cove	0.011	0.038	0.140	--	0.178	0.162	0.000	0.340	--	--
Town Cove	0.953	5.426	26.169	--	31.595	5.230	59.744	96.568	0.49-0.60	--
System Total	**2.488**	**10.240**	**42.953**	**--**	**53.192**	**18.252**	**134.079**	**205.523**	**--**	**0.45**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings
[5] atmospheric deposition to embayment surface only
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 2001 – 2004 data, ranges show the upper to lower regions (highest-lowest) of an sub-embayment. Individual yearly means and standard deviations in Table VI-1.
[8] Threshold for sentinel sites located in Town Cove at water quality station WMO-27 (0.45 mg/L) and in Salt Pond (0.45 mg/L)

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Nauset Harbor estuary system.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
SYSTEMS						
Nauset Marsh	10.729	10.729	11.252	46.838	68.819	0.0%
Salt Pond	5.014	1.196	0.299	14.201	15.696	-76.1%
Woods Cove	0.745	0.745	0.241	4.657	5.643	0.0%
Mill Pond	4.932	4.932	1.068	3.219	9.219	0.0%
Rachel Cove	0.178	0.178	0.162	0.000	0.340	0.0%
Town Cove	31.595	11.968	5.230	41.520	58.718	-62.1%
System Total	**53.192**	**29.748**	**18.252**	**110.436**	**158.435**	**-44.1%**

(1) Composed of combined natural background, fertilizer, runoff, and septic system loadings.
(2) Target threshold watershed load is the load from the watershed needed to meet the embayment threshold concentration identified in Table ES-1.
(3) Projected future flux (present rates reduced approximately proportional to watershed load reductions).
(4) Sum of target threshold watershed load, atmospheric deposition load, and benthic flux load.

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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 Nauset Harbor Estuarine System and supported the application of the Linked Watershed-Embayment Management Modeling Approach to Determine Critical Nitrogen Loading Thresholds for this system. Without these stewards and their efforts, this project would not have been possible.

Through the efforts of the Wastewater Management Steering Committee and the Program Technical Team, the Orleans Water Quality Monitoring Program was initiated in 2001 and has continued through 2010 as a collaborative effort between the Coastal Systems Program at the School for Marine Science and Technology-UMass and the Town and Citizens of Orleans. The Program is coordinated by the Orleans Planning Department, George Meservey, Director.

First and foremost we would like to recognize and applaud the significant time and effort in data collection and discussion spent by the volunteers of the Town of Orleans Water Quality Monitoring Program and Water Quality Task Force, without whose effort Town-wide monitoring would not be possible. These individuals have given of their time to collect nutrient related water quality from this system, needed for the present analysis. Also, of particular note are George Meservey of the Orleans Planning Department and Gussie McKusick of the Orleans Wastewater management Steering Committee, who were instrumental in instituting and initially coordinating the program and the present Coordinator, Judy Scanlon, who has worked hard to continue this important effort for the Town. Similarly, many in the Town of Orleans helped in this effort since 2001, but particularly the members of the Wastewater Management Steering Committee, the Town Planning Office and members of the Board of Selectman.

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I. INTRODUCTION

The Nauset Harbor Estuary, comprised of Nauset Marsh, Town Cove and a series of small terminal basins (Salt Pond, Wood Cove, Mill Pond), is located within the Towns of Orleans and Eastham on Cape Cod, Massachusetts. The system has an eastern shore bounded by a narrow barrier beach, Nauset Beach, separating the Harbor and marsh from the Atlantic Ocean, with which it exchanges tidal waters. The Nauset Harbor Estuary is one the largest embayment systems on Cape Cod and is comprised of open water areas (Nauset Harbor, Town Cove and 3 small terminal basins) as well as a large tidal salt marsh, Nauset Marsh, which has filled most of the lagoon that formed behind Nauset Barrier Beach (Figure I-1). The watershed contributing nitrogen to the waters of the Nauset Estuarine System is distributed among the Towns of Orleans, Eastham and Brewster. Restoration of impaired habitat within the estuary will depend upon the coordinated efforts of these municipalities and their citizens.

The present configuration of the Nauset Harbor Estuarine System (also sometimes termed an embayment system) results from a combination of glacially dominated geologic depositional processes, with continuing reworking by coastal processes. In addition, human activities have had significant effects on estuarine function. Overall, the Nauset Harbor System is a composite or complex estuary comprised of a salt marsh filled lagoon formed behind a barrier beach, Nauset Beach, and smaller open water tributary basins. Nauset Beach consists of sands and gravel eroded from the Ocean shore of the upper Cape and transported southward by littoral drift. This large coastal lagoon contains both emergent marsh, tidal channels and salt marsh dominated open water areas, the largest being Salt Pond Bay and Nauset Bay. The lagoon represents more than ~1/2 of the estuarine area and habitat. Tributary to the large outer lagoon are open water basins that appear to have been formed by seawater entry to kettles, as sea level rose in the post-glacial period. These terminal basins are frequently deeper than the lagoon and include, Town Cove, Wood Cove[1], Salt Pond and Mill Pond. In some cases the connection of these terminal basins to tidal flow may have historically been enhanced by human activities. The Nauset Harbor System is a relatively “young” estuary and coastal feature that required significant post glaciation sea-level rise and the formation of the barrier beach, occurring on the order of 2500-4000 years b.p.

The beach and the inlet are very dynamic geomorphic features, due to the influence of littoral transport processes. The Nauset Estuary presently exchanges tidal water with the Atlantic Ocean through a single inlet situated in the more northern portion of the system. While the formation of the Nauset Harbor / Marsh system was dependent upon coastal processes which formed the barrier beach to form the lagoon and tidal channels through the marsh, the estuary continues to be affected by these same coastal processes as they alter both the length of the spits (Nauset Spit-Eastham to the north and Nauset Spit-Orleans to the south) and the location of the tidal inlet. Similarly, Nauset Beach can be significantly altered by periodic storms and was breached as recently as 1972 in the Eastham portion of the spit. The effect of these processes is not only to alter tidal dynamics, but also to partially control the quality of the habitats within the estuary. Changes in hydrodynamics wrought by inlet dynamics is a key factor in determining the effects of watershed nitrogen loading on estuarine health (see Sections V & IX). To the extent that the inlet becomes restricted or migrates north or south and tidal flushing is reduced, nitrogen loading impacts will be magnified over present conditions. Any long term habitat management plan for the Nauset Estuarine System must recognize the importance of inlet dynamics and include options to maintain the present (or other suitable)

[1] The formation of Wood Cove from seawater rise entering a kettle is less certain given its present bathymetry.

hydrodynamic conditions as evidenced by the creation of a new inlet in the Pleasant Bay system in 2007.

Figure I-1. Study region proximal to the Nauset Estuarine System for the Massachusetts Estuaries Project nitrogen thresholds analysis. Tidal waters enter the system through a single tidal inlet to the Atlantic Ocean. Freshwaters enter from the watershed primarily via groundwater and 1 small surface water discharge to Town Cove. The main basins forming most of the estuarine area are Nauset Marsh (inclusive of the salt marsh basins of Nauset Bay and Salt Pond Bay), Town Cove, Salt Pond Bay, Wood Cove and Mill Pond.

The Nauset Estuarine System is situated within a watershed that includes glacial outwash plain and ice contact deposits (Nauset Height ice-contact deposits). The aquifer is comprised of outwash sand and gravel of the Eastham Plain, with a kame belt to the north and west and sand

and gravel and scattered boulders overlying eroded Pleistocene sand, gravel and clay to around Town Cove and to the south. This material was deposited after the retreat of the South Channel Lobe of the Laurentide Ice sheet ~15,000 years ago. In fact, the Nauset system is situated in the location of 2 sub-lobes of the South Channel lobe, from which these deposits were generated (Oldale, 1992). In general, the material is highly permeable due to its composition: well sorted medium sands to coarse pebble sands and gravels. As such, direct rainwater run-off is rather low, with most freshwater inflow to the estuary via groundwater discharge or groundwater fed surface water flow. At present there is only one small stream, discharging primarily aquifer recharge (e.g. groundwater) to the estuary (Town Cove). Therefore, the vast majority of freshwater from the watershed enters the Nauset Estuarine System through direct groundwater seepage along the western shore. Like all Cape Cod estuaries, the Nauset Estuary acts as a large mixing zone for terrestrial freshwater inflow and saline tidal flows. However, the salinity distribution within the estuary varies with the volume of freshwater inflow and the tidal exchange with the marine waters of the adjacent Atlantic Ocean. Given the large tidal flows and volumetric exchange, there is presently only minor dilution of salinity throughout most of the estuary.

The Nauset Estuary, along with its associated terminal sub-embayments, constitutes an important component of the natural and cultural resources of Cape Cod and the Towns of Orleans, Eastham and Brewster. As such the Town of Orleans has worked steadily over many years to monitor the water quality conditions in the Nauset Estuarine System and worked with Institutions such as the Woods Hole Oceanographic Institution and the National Park Service to better understand how the Nauset system functions and how it should be managed to safeguard the resource in the long term.

As is the case with the majority of coastal systems on Cape Cod, the primary ecological threat to the Nauset Harbor resource is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters has been greatly increased over the past few decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to this and other outer Cape embayment systems, such as nearby Pleasant Bay and most embayments in southeastern Massachusetts, results primarily from on-site septic treatment and disposal of wastewater. The Towns of Orleans, Eastham and Brewster, like other towns on Cape Cod, have grown both seasonal and year-round populations over the past 60 years with more than a 4 fold increase in population and an even greater increase in nitrogen loading. None of the towns in the watershed have centralized wastewater treatment and the Tri-Town Septage Treatment Facility located in the Town of Orleans and serving the Town of Eastham and Brewster only processes pumped septage. Residential areas and most commercial properties throughout Orleans, Eastham and Brewster are essentially serviced by on-site septic treatment and disposal systems. As existing and probable increasing levels of nutrients impact the receiving coastal embayments water quality degradation will continue and potentially accelerate, with further harm to invaluable environmental resources.

The large shoreline and small terminal sub-basins of the Nauset Estuarine System greatly increases the potential for direct groundwater discharges from homes situated on the shore and decreases the travel time of groundwater from the watershed recharge areas to estuary. 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, the more enclosed basins within the inner reaches of the system such as Town Cove, as well as terminal sub-embayments such as Salt Pond, Wood Cove and Mill Pond are at risk of eutrophication from high nitrogen loads entering mainly via direct groundwater seepage and, to a much smaller extent, to surface water inflows from adjacent sub-watersheds (Figure I-1).

As the primary stakeholders to the Nauset Estuarine System, the Towns of Orleans and Eastham were among the first communities to become concerned over perceived degradation of their habitat. The Town of Orleans (via the Planning Office) has long recognized the potential threat of nutrient over-enrichment of the Town's coastal embayments. As such, a comprehensive water quality monitoring program was developed as a coordinated effort between municipal staff and committees and volunteer stewards. While the aquatic resources of the Nauset System reside almost entirely within the Towns of Orleans and the Town of Eastham, the Town of Orleans took the lead in the establishment and conduct of the water quality monitoring of this estuary. The Orleans Water Quality Monitoring Program was conducted in a manner consistent with other water quality programs throughout the region so as to provide consistent comparable system-wide data, required for the application of the MEP Linked Watershed-Embayment Management Modeling Approach.

The common focus of the water quality monitoring efforts undertaken by the Towns of Orleans and Eastham has been to gather site-specific data on the current nitrogen related water quality throughout the Nauset Estuarine System, such as Nauset Marsh, Town Cove, Salt Pond, Wood Cove, Mill Pond and determine the relationship between observed water quality and watershed nitrogen loads. This multi-year effort has provided the baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. The combined water quality data sets from the water quality monitoring program for the Nauset Estuary each form a baseline from which to gauge long-term changes as watershed nitrogen management moves forward. Although the system-wide monitoring continued for only ~4 years, the continued monitoring of key stations demonstrated that water quality within the estuarine basins was not changing significantly over the period of study analyzed by the MEP. These data allowed the MEP to prioritize the Nauset Estuary for this next step in the Bay's restoration and management process.

The MEP effort builds upon the efforts of the water quality monitoring program, and previous hydrodynamic and water quality analyses, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Nauset Estuarine System and its multiple sub-basins.

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 Towns of Orleans, Eastham and Brewster for restoration of the impaired habitats within the Nauset System. 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 a 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 Towns to develop and evaluate the most cost effective nitrogen management alternatives to restore these valuable coastal resources which are currently being degraded by nitrogen overloading.

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 (as is the case with the Towns of Orleans and Eastham) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries.

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

The Massachusetts Estuaries Project represents the next generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (MassDEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts.

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region's coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the municipalities and 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 outlines 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.

As part of the overall MEP effort, the evaluation and modeling approach will be used to assess available options for meeting selected nitrogen goals, protective of embayment health.

The major 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 70 out of 89 embayments in southeastern Massachusetts with municipal stewards,
- 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 planning and management 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 embayment circulation model depending on embayment structure (or 3D as necessary);
- 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. 50 embayments throughout southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach's greatest assets are its ability to be parameterized with embayment specific data, clearly calibrated and validated, it is robust as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options and 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-2). 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

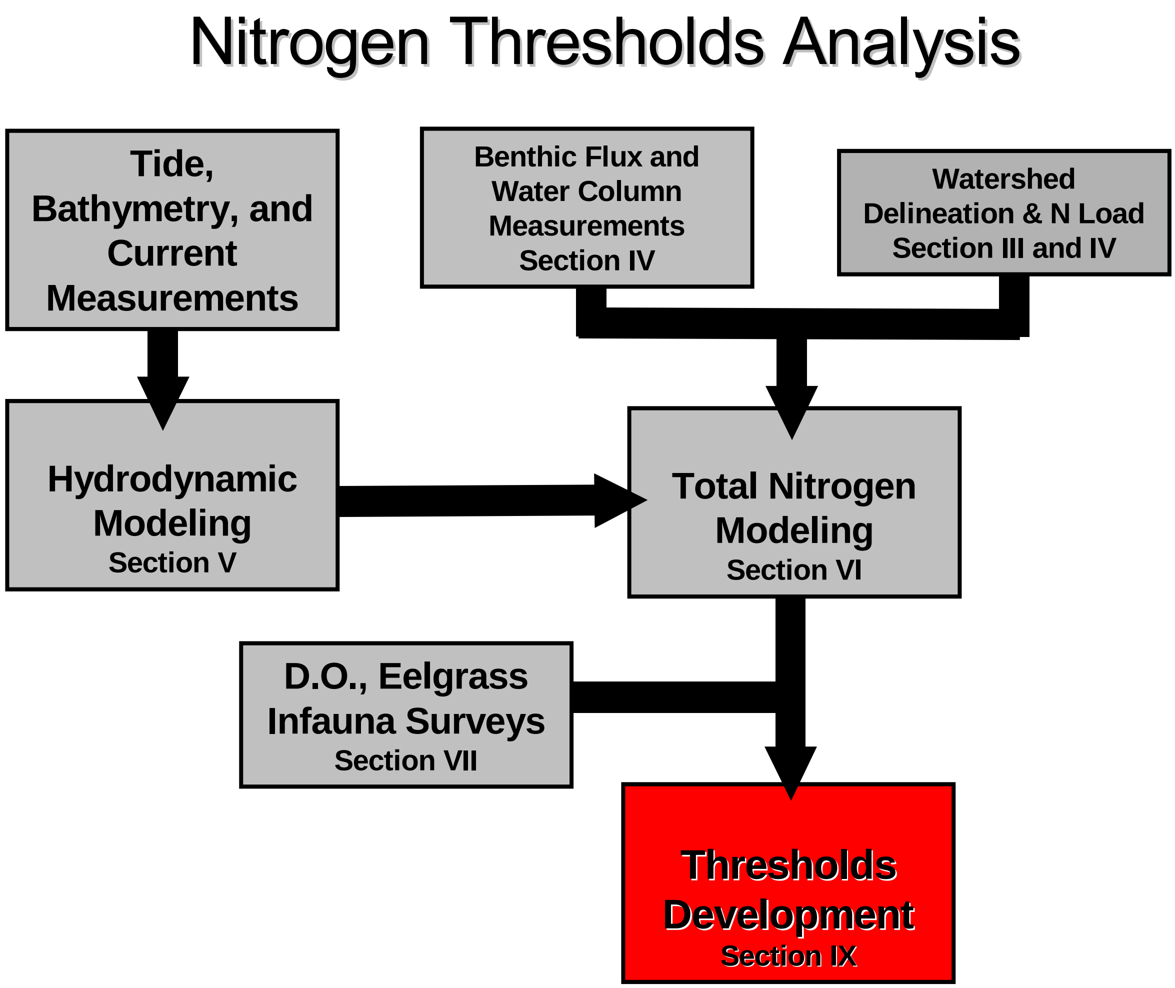


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

I.2 SITE DESCRIPTION

The Nauset Estuary is one of the largest estuarine systems on Cape Cod and is comprised of more than 2,200 acres of estuarine habitat (salt marsh, tidal flats, and saltwater open-basins. The system contains large areas of salt marsh, among one of the largest salt marshes on Cape Cod along with Barnstable Great Marshes. The system is situated on the eastern shore of outer Cape Cod with the main basin (Nauset Marshes) formed as a lagoonal estuary behind the barrier beach (Nauset Beach) and generally oriented in a north – south manner with one large inlet located at the center of the system. The system is a complex estuary or composite estuary with a large lagoon and tributary terminal open water basins (Town Cove, Wood Cove, Salt Pond, Mill Pond) along the western shore of the system. The inlet provides Atlantic Ocean source water to the overall Nauset Estuarine System. The inlet can be significantly affected by longshore sand transport (north to south), where shoaling can impede hydrodynamic exchange at the mouth and, in the case of extreme events, close an existing inlet and open a new one, as was the case for Pleasant Bay in 1987 when the barrier beach was breached and the New inlet opened up. The barrier beach that forms the Nauset Estuary is a similarly dynamic land form. The Nauset System has historically alternated from a one inlet system to a two inlet system, like adjacent Pleasant Bay. The existing inlet to the

Nauset Harbor system is a natural inlet and has not been stabilized with riprap and is greatly influenced by shifting sands. There is no formal navigational channel that is regularly maintained and shoals are abundant in the vicinity of the inlet and depths vary significantly. Depths throughout the Nauset Harbor system vary significantly due to the tidal salt marsh characteristics of the system in combination with the open water areas with depths greater than 20 feet. At low tide large areas of Nauset Harbor and the marsh system are exposed tidal flats with little to no water (e.g. Nauset Bay in the uppermost reaches of the system).

The inlet to the Nauset Harbor system has gone through significant transformations over the last century as a result of intense coastal processes (refer to Section V on hydrodynamics). In the past three decades, Nauset Spit-Eastham was breached during a northeast storm that occurred in 1972, thus forming what was considered a temporary inlet to the north of the main inlet that is more centrally located in the system. The tidal exchange of waters from Nauset Harbor with the Atlantic Ocean water is driven by a moderate tidal difference between the estuary and the ocean of approximately 5 ft (Section V). Since the water elevation difference between the Atlantic Ocean and Nauset 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, south shore of Falmouth is 1.5 ft).

For the MEP analysis, the Nauset Estuarine System was analyzed in totality with all the associated tributary basins contributing to the estuarine dynamics of the overall system. The Nauset Estuary was partitioned into three general embayment groups: 1) the salt marsh basins of Salt Pond Bay and Nauset Bay, 2) the coves and drowned kettles along the western shore (e.g. Town Cove, Wood Cove, Mill Pond and Salt Pond, 3) the mid and lower portions of the estuary that are primarily tidal marsh and associated channels. Similar to other embayment systems throughout the MEP study area (e.g. Pleasant Bay system, Popponesset Bay, Three Bays) Nauset is an estuary with freshwater input mainly in areas distant from the tidal inlet (primarily through groundwater discharge) and tidal exchange of marine waters from the Atlantic Ocean (tide range of approximately 5 ft) at its central inlet. Town Cove which receives freshwater discharge via a very small stream is predominantly a groundwater fed basin. The high rate of tidal exchange and the entry of freshwater all along the western shore (perpendicular to the long axis of the estuary) combine to minimize the salinity gradients in the open basins. Salinity in the system generally ranges from approximately 32 ppt at the inlet to not less than 29 ppt in the headwaters of its sub-embayments.

Overall, the Nauset Harbor system is a shallow mesotrophic, moderately nutrient impacted, (with some eutrophic sub-embayments) coastal embayment system on the eastern coast of Cape Cod. The structure of the watershed and estuary tend to reduce the sensitivity of this system to nitrogen loading, as it maintains a relatively high water turnover and has a relatively low area of watershed per area of estuarine surface (~3:1) compared to many estuaries in southeastern Massachusetts. In addition the large salt marsh area has a relatively low sensitivity to nitrogen loading, so that the main areas of concern are primarily the terminal open water basins.

As management alternatives are being developed and evaluated, it is important to note that nitrogen loading and tidal exchange within each component basin is the primary factor controlling habitat health in that sub-basin. The quality of the inflowing waters from the adjacent water body is the other. For example, the nitrogen loading to each of the western terminal basins affects the health of the down-gradient main basin comprising the Nauset Marshes. Most of the nitrogen entering this lagoon, first passes through a sub-embayment such as Town Cove on its way to the main basin on ebbing tides and high levels of nitrogen in the main basin will affect the nitrogen dynamics of the terminal basins as the water enters on flood tides. The result is that the restoration of nitrogen impaired sub-embayments to the Nauset System require both “local” or contributing area specific nitrogen management, as well as management of nitrogen levels within the watershed of the larger “regional” main basins that make up the Nauset Marsh and its sub-basins. Similar to smaller estuarine systems, the highest levels of nitrogen enrichment are found in the terminal sub-basins rather than in the larger lagoon which exchanges water directly with the Atlantic Ocean. It is these small tributary basins that presently show the greatest nitrogen related impairment of habitat quality within in this large and dynamic estuarine system.

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

Unfortunately, most of the smaller sub-basins to the Nauset Estuary (Town Cove, Salt Pond, Nauset Bay sub-systems) are near or beyond their ability to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated within these basins and historic eelgrass areas have diminished significantly. The result is that nitrogen management within this estuary is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed “eutrophication” and when the nutrient loading is primarily from human activities, “cultural eutrophication”. Although the influence of human-induced changes has increased nitrogen loading to the system and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within the Nauset Estuarine System could potentially occur without anthropogenic 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 Nauset Estuary; 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 Nauset Estuary and all of its component basins. 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 was computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic 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 by USGS using a modification of the Monomoy model for sub-watershed areas designated by MEP. Almost all nitrogen entering the Nauset Estuarine System is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Atlantic Ocean source waters and throughout the Nauset Estuary was taken from the water quality monitoring programs run by the Town of Orleans (associated with the Coastal Systems Program at SMAST). Measurements of current salinity and 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 approach to the Nauset Estuarine System for the Towns of Orleans, Eastham and Brewster. A review of existing studies related to habitat health or nutrient related water quality is provided in Section II with a more detailed review of prior hydrodynamic investigations in Section V. 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 nitrogen recycling associated with the 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 Town and Cape Cod Commission data and offshore water column nitrogen values were derived analysis of Atlantic Ocean waters of the upper Cape. (Section IV and VI). 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 and the results of a benthic analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of the embayment as described 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 salt pond or cove. This latter assessment represents only one of many solutions and is produced to assist the Towns in developing a variety of alternative nitrogen management options for the Nauset Estuarine System. Finally, any additional analyses of the Nauset Estuary relative to potential alterations of circulation and flushing from the opening of a second inlet or changes in watershed based nutrient inputs from load reducing alternatives would be presented in Section IX.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

Nutrient additions to aquatic systems cause shifts in a series of biological processes that can result in impaired nutrient related habitat quality. Effects include excessive plankton and macrophyte growth, which in turn lead to reduced water clarity, organic matter enrichment of waters and sediments with the concomitant increased rates of oxygen consumption and periodic depletion of dissolved oxygen, especially in bottom waters, and 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, which are dependant upon these highly productive estuarine systems as a habitat and food resource during migration or during different phases of their life cycles. This process is generally termed “eutrophication” and in embayment systems, unlike in shallow lakes and pond, it is not necessarily a part of the natural evolution of a system.

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

These tools for predicting 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 specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Nauset Estuarine System (inclusive of Town Cove). 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.

Coastal Processes and Hydrodynamics of the Nauset Estuary, Woods Hole Oceanographic Institution.

A number of studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Nauset Harbor System over the past two decades. As far back as the early 1980’s, researchers have been interested in documenting the dynamic coastal processes of Nauset Beach. Speer and Aubrey produced a Woods Hole Oceanographic Report (WHOI-82-40, 92 pp.) that summarized beach changes at Nauset Inlet from 1670 to 1981. Subsequently, Stephen Leatherman and Robert Zaremba undertook an investigation of the dynamics of Nauset Spit, published in the Bulletin of the Geological Society of America (vol. 97,

p. 116-124, 1986). The analysis concluded that the Nauset Spit Barrier Beach system is extremely dynamic and that the spit is generally retreating landward due to inlet dynamics and overwash processes. Given the dynamic nature of the barrier beach and the inlet as well as the frequency of overwash events during strong winter storms, management of the Nauset Estuary must take into consideration potential alterations to the natural flushing capacity of the system, as was also the case recently for the southern portion of Nauset Beach which forms the main lagoon of Pleasant Bay.

Nearly a decade after Leatherman and Zaremba summarized the dynamics of Nauset Spit, another analysis of changes in the Nauset Barrier Beach was completed by scientists at the Woods Hole Oceanographic Institution in 1998 (*Beach Changes and Management Options for Nauset Barrier Beach and Orleans Town Beach*, WHOI-98-10). This report was produced for the Town of Orleans in order to examine beach erosion issues and its effect on the flooding of Aspinet Road, the health effects of erosion of the septic system at the Town Beach to the south of Nauset Marsh Inlet and the fate of New Island in the Nauset Estuarine System and its contribution to the stability of the South Spit of the Nauset Barrier Beach. This report indicated that extensive previous research on erosion rates where consistent with the findings of the 1998 WHOI investigation and that the entire beach system from Coast Guard Beach to the north of the Nauset Inlet to Pochet Neck to the south has been undergoing significant erosion from the 1930's to the time of the 1998 study. This is certainly still the case. The 1998 report also indicated that beach erosion rates were higher at the Nauset Inlet. As in Pleasant Bay to the south, the dynamic nature of the Nauset inlet should be considered in the development of a nutrient management plan for the Nauset Estuary.

In advance of completing the hydrodynamic modeling of the Nauset Estuarine System, the MEP Technical Team also reviewed the findings of another Woods Hole Oceanographic Report released in 1997 which investigated the tidal circulation and flushing characteristics of the Nauset Marsh system (WHOI-97-11). The report was produced for the Town of Orleans and the National Park Service (Cape Cod National Seashore), as these are the primary stakeholders charged with the management of the associated estuarine resources. The main objective of the study was the quantification of estuarine circulation and residence times for water in the marsh system under two differing inlet scenarios, a single inlet, as existed at the time of the study as well as a dual inlet scenario that existed from 1992-1996. Unfortunately, the offshore tide gauges utilized for this study failed during both deployment periods, and the model was forced with predicted rather than measured offshore tides, likely compromising the results of the modeling effort. The morphological change from a dual to a single inlet system was considered in the context of changes in residence time in sub-embayments of the overall system. These residence times were then to be used by the Cape Cod Commission in order to assess which portions of the system would be particularly vulnerable to habitat impairment from watershed nitrogen inputs given assumptions for build-out within the associated watershed.

Residence times were evaluated for twelve cases, to demonstrate the range of residence times that can be defined based on varying assumptions. Based on these various inputs, assumptions and calculations, the investigators found that residence times for Salt and Mill Pond under conditions of a single inlet are the longest of the various sub-embayments. Water in Town Cove was found to be relatively quickly renewed, though not as fast as the main channels serving the system. Flow patterns under the dual-inlet condition did seem to be partitioned well, with the northern inlet serving the northern part of the system and the southern inlet serving the southern part of the system, with little hydrodynamic communication between the two divisions. As would be expected, the investigators found that the hydrodynamic characteristics of the dual inlet system results in shorter residence times than under a single inlet. The important point to consider is that while this historic circulation study is a good reference, morphologic changes occur rapidly in these outer Cape Cod systems. The issue of circulation, flushing and residence times needs to be re-evaluated on a regular basis in order to assess the system based on “real world” conditions.

This study provided one of the first formal evaluations of the dynamics of the Nauset Beach/Nauset Estuary to serve as a basis for evaluating the effects of increased nutrient loading and potential for eutrophication of the system arising from development in the watershed around the Nauset embayment. As has been undertaken by the MEP Technical Team, the investigators recommended periodic re-examination of circulation and residence times due to rapid and significant morphological changes that can occur in this system. In addition, salinity profiles performed as part of the study indicated that the Nauset Estuary system is vertically well-mixed, making use of a depth-averaged hydrodynamic model an appropriate tool for analysis of tidal circulation. To assist with the hydrodynamic model development required as part of the MEP, the Woods Hole Oceanographic Institution information was sought; however, after repeated efforts to contact the Principal Investigator (Dr. David Aubrey, currently the CEO of Aubrey Consulting, Inc./Woods Hole Group, Inc.), the MEP technical team moved forward with an independent analysis.

Another Woods Hole Oceanographic Institution study of the Nauset Estuary system is presently underway (Principal Investigator: Dr. Donald Anderson) regarding the occurrence of red-tide in the Nauset Marsh Estuary and its rrelation to increased nutrient loading. The project is combining detailed field and laboratory studies to examine the population dynamics of harmful algal blooms (HABs) in the Nauset Marsh Estuary (NME), and relate hydrodynamics, and groundwater nutrient fluxes to HAB duration and intensity using an existing physical-biological numerical model. In Massachusetts, paralytic shellfish poisoning (PSP) caused by red tides is annually recurrent along the coastline, including within a number of small embayments and salt ponds on Cape Cod. One such system within the Cape Cod National Seashore is the salt marsh dominated NME. Since the 1970’s, the NME has experienced annual episodes of *Alexandrium* blooms that are initiated and most intense in the landward extensions of the estuary. These are also the locus of maximum groundwater and associated nutrient discharge to the system. According to work being undertaken by Dr. Anderson, the characteristics of the PSP problem in the NME have changed in a dramatic and negative manner over the last two decades. PSP occurred in Salt Pond (NME) in 8 of 17 years (48%) from 1975 to 1991, and then in 18 of the last 19 years (95%).

Transient Simulations of Nitrogen Load for a Coastal Aquifer and Embayment, Cape Cod, MA. (USGS 2007).

The United States Geological Survey (USGS) conducted a trial application of a time-varying, multi-species, modular, three-dimensional transport model (MT3DMS) which was developed to simulate groundwater transport of nitrogen from increasing sources on land to the shore of the Nauset Estuary, a coastal embayment of the Cape Cod National Seashore. In this study, simulated time-dependent nitrogen loads at the coast were used to correlate with current observed coastal eutrophic effects to predict current and ultimate effects of development, and to predict loads resulting from source remediation. In the study, a time-varying nitrogen load, corrected for subsurface loss, was applied to the land subsurface in the transport model based on five land-use coverages documenting increasing development from 1951 to 1999. USGS scientists simulated nitrogen loads to Nauset Marsh which increased almost 20 fold from 1930 to 2001 and then 1.8 times again by 2100, assuming future nitrogen sources constant at the 1999 land-use rate. The simulated nitrogen load per area of embayment was 5 times greater for

Salt Pond, a eutrophic landward extension of Nauset Marsh, than for other Nauset Marsh areas. Sensitivity analysis indicated that load results were little affected by changes in vertical discretization and annual recharge but much affected by the nitrogen loss rate assumed for a kettle lake down gradient from a landfill, where 100% nitrogen loss was anticipated. Analysis focused on aquifer processes.

The Coastal Impact of Groundwater Discharge: an assessment of anthropogenic nitrogen loading in Town Cove, Orleans, MA. Woods Hole Oceanographic Institution, November 1983.

A year-long investigation of nitrogen transport and transformation within the watershed and estuarine waters of Town Cove was undertaken primarily to guide the Town of Orleans in deciding between a septage treatment and sewerage treatment facility. A primary research goal was to determine the role of the watershed nitrogen load in the cultural eutrophication of the Cove and the roles of particulate deposition and remineralization in the productivity of the estuary. Measurements included groundwater nitrogen levels, system freshwater inflow, sediment nitrogen release, phytoplankton productivity and its limitation within the Cove and the potential impacts of increased nitrogen loading to Namskaket Marsh through surface disposal of treated septage effluent from a potential facility (now Tri-Town).

The conclusion of the project was that shading due to phytoplankton blooms sometimes limited the sensitivity of Town Cove waters to additional nitrogen and phosphorus inputs; that the Cove is serving as a depositional basin which enhances nitrogen release from the sediments during summer; that the central basin had periodic anoxia of bottom waters which resulted in the seasonal loss of benthic animal communities. Inorganic nutrient data could not be used "in a diagnostic fashion to estimate the degree of eutrophication in the water body". This results from the rapid incorporation of inorganic nutrients into phytoplankton biomass. The results would indicate that significant nutrient reduction would be needed to restore the system.

The report notes benthic animal communities within Town Cove and the seasonal bottom water oxygen declines. Groundwater discharge and nitrogen levels were highly variable, with a significant discharge through seeps along the north shore of Town Cove. Differences in nitrogen loading rates estimated by groundwater sampling in this study and the watershed approach of the Cape Cod Commission (see below) likely result from the spatial heterogeneity of the discharge and the relatively few groundwater samples collected. High quality summertime inorganic nitrogen and phosphorus levels, chlorophyll a and particulate carbon and nitrogen were measured on multiple occasions. Town Cove is enriched in phytoplankton and nitrogen over offshore coastal waters year-round. Phytoplankton production measurements were performed only near the shore at the Cove's head and at the tidal outlet. However, inorganic nitrogen levels remain low and particulate nitrogen levels high within the waters of the central Cove and productivity incubations indicated very high levels of phytoplankton growth. Interestingly the study noted that summertime nitrogen release from the sediments may exceed the nitrogen inputs from the watershed and therefore must be included in any nitrogen balance.

Groundwater Nutrient Concentrations Around Nauset Marsh. Final Report and Data Appendix A, National Park Service, Department of Interior, 1994.

The report describes the methods and results of the first phase of a larger study. The first phase was a survey of shoreline groundwater nutrient concentrations (20 cm-40 cm below the water table along the high tide line) to be used for selection of study sites for hydrologic and denitrification measurements. Groundwater (<2ppt by refractometer) was collected for assay of inorganic nitrogen (ammonium, nitrate) and phosphorus (ortho-phosphate) concentrations at 14 shoreline locations around Nauset Marsh within the Cape Cod National Seashore. Samples were collected at 1 to 5 meter intervals along the high tide line. Nitrate levels within most sites were highly variable, frequently ranging over 100 fold, making comparisons to upland development problematic. No ground water flow information was provided.

This phase of the effort was "not intended nor should the data be interpreted as a systematic survey of ground water quality around the Nauset system". A future effort is referred to in the first phase which would assess the importance of microbial denitrification within the sub-tidal and inter-tidal sediments of the receiving marine systems and the role of specific flow paths and sediment types. Five of the fourteen sites were recommended for the future work (1-Salt Pond Bay, 2-Salt Pond, 3-Weeset, 4-Shore Garden and 5-Eldredge, 4&5 are Orleans shores). The referred to denitrification studies are presented below. Based on the first phase work, it was determined that groundwater nitrate levels were elevated in developed areas, similar to all other areas of Cape Cod. Nitrate levels typically reached 200 - 500 uM at each site influenced by developed uplands. However, the high variability of nitrate levels within each measurement site limited the usefulness of the approach. The study does provide potentially useful site-specific information on nutrient levels in groundwater originating from undeveloped areas which is required for the land-use analysis undertaken by the MEP.

The Role of Sediment Denitrification in Reducing Groundwater-Derived Nitrate Inputs to Nauset Marsh Estuary, Cape Cod, Massachusetts. B.L. Nowicki, E. Requintina, D. Van Keuren, J. Portnoy, Estuaries (1999) 22:245-259.

Five sites within the Nauset Inlet System were assayed seasonally for sediment denitrification rates to gauge their potential impact on reducing groundwater transported nitrate inputs to estuarine waters. The five sites were selected within the Park Service matrix (see above study), to represent a range of nitrate levels and sediment types at the groundwater discharge sites.

Based on the study, there was no relationship between measured denitrification rates and associated groundwater nitrate concentrations. In fact, denitrification supported by groundwater nitrate was found to be small. Most denitrification was fueled by the coupled nitrification/denitrification within the sediment system. Denitrification was related with sediment organic matter content and varied seasonally with organic content and temperature. The authors concluded that "denitrification did not contribute significantly to the direct loss of nitrate from incoming groundwater at Nauset marsh estuary. Therefore most groundwater nitrate reaches the estuary.

Coastal Nitrogen Loading Project, Interim Report September 2000, Water Resources Office, Cape Cod Commission.

This evaluation of the Nauset system included a watershed nitrogen loading assessment and tidal flushing study, but did not have confirmatory measured water quality data. Watershed nitrogen loads under present and build-out conditions were developed. Critical nitrogen loading limits were developed based upon a screening approach and a flushing study conducted separately. However, the flushing study failed to recover data from the offshore gauge which "drives" the water exchange, so the flushing estimates are approximate. Flushing was evaluated both for a single and dual inlet (based upon WHOI Study noted above). Watershed delineations were based upon data from the Wellfleet Harbor Project and Orleans Water table Measurement Study.

The whole Nauset Inlet System and its major sub-systems, Nauset Marshes (main basin), Town Cove, and Mill Pond were determined to be below their critical nitrogen limits. In contrast, Salt Pond is currently over its critical nitrogen loading limit. About 60% of the Salt Pond watershed nitrogen input is from the landfill (capped in 1997). No ecological data were available to verify the conclusions.

Basic information on land-use (GIS) from this study was incorporated directly into the present MEP program. The watershed delineations were used for comparison to the USGS delineations for the MEP (Section III). Portions of the flushing study have been directly incorporated into the present effort and this is reflected in the hydrodynamic portion of this report, see Section V. However, the tide gauges needed to parameterize the MEP model were deployed successfully during the summer of 2001. This was necessitated by the failure of all of the offshore gauges in the earlier efforts.

Statistical Analysis of Multi-year Water Quality Monitoring Data 2003-2010 (Fiegel, 2011).

This unpublished and un-reviewed, yet widely distributed, statistical analysis was undertaken by a citizen of the Town of Orleans on the water quality monitoring data collected in the Nauset Marsh/Harbor system between 2003 to 2010. The data were generated by the Town of Orleans Water Quality Monitoring Program described below. The analysis had 3 major findings: "(1) The dissolved oxygen levels throughout the Estuary exceed the State water quality criterion of 6 milligrams per liter (mg/L) with the exception of samples from the bottom of Mill and Salt Ponds, and at the bottom of the Yacht Club (closed end of Town Cove). This indicates that the Estuary waters have a healthy oxygen environment, (2) Nitrogen concentrations at many of the sampling stations in the Nauset Estuary tend to be lower than the median concentration at the Atlantic Ocean sampling station. This observation indicates that nitrogen concentrations throughout the Estuary may not be elevated because of septic nitrogen. Even though the sampling locations at Mill and Salt Ponds and at the closed end of Town Cove tend to show much higher nitrogen concentrations in the bottom samples than in the middle or surface samples; it is not clear that septic nitrogen is the cause, (3) The MEP water quality monitoring measurements do not seem to support the assertion that a significant reduction in septic nitrogen discharge to the Estuary will improve water quality throughout the system, especially, as dissolved oxygen is already in a healthy state throughout the surface and middle depths."

The conclusion that DO levels, as measured, exceed water quality standards, is incorrect as the analysis is based upon average DO conditions, not the periods of low oxygen that are the basis of stress to estuarine animals. Average DO values are not appropriate in ascertaining compliance with standards. Additionally, the Surface Water Quality Standards (314 CMR 4.00) state that for Class SA waters DO "shall not be less than 6.0 mg/L". It is the period of lower values that is of concern because short periods of low DO are generally sufficient to result in adverse ecological consequences for the system. The Orleans Monitoring Program data show multiple instance of low oxygen throughout the estuarine basins. However, traditional sampling programs typically do not capture the lowest oxygen levels due to the high frequency variation that DO exhibits in many estuarine basins. Therefore, the MEP analysis uses information from both monitoring grab samples in concert with the time series DO measurements to determine the oxygen status of a system. In addition the statistical analysis downplayed the low oxygen levels in bottom water and it is bottom water that is in direct contact with the sediments, the habitat for benthic animals that play key roles in the estuarine food web.

The analysis correctly concluded that the offshore boundary station is showing high nitrogen levels, higher than some of the basins within the Nauset Estuary. The offshore station is established to set boundary conditions for modeling and was chosen to represent offshore waters which are relatively uncontaminated from land based nitrogen. Throughout the MEP region, these waters have been located in the Atlantic Ocean, Vineyard Sound, Nantucket Sound or the open waters of Buzzards Bay and generally have displayed total nitrogen levels ranging from 0.25 to 0.31 mg/L. The median levels at the Nauset Offshore Station (WMO-41) were very high (~0.6 mg TN/L), 2 times higher than all offshore sampling stations in the region. In contrast the TN levels within the Nauset Estuary are about average of tidal basins on Cape Cod. The conclusion of the MEP was that the offshore station was anomolous, partially confounded by the timing of the sampling and the position of the station relative to the tidal inlet. This is supported by the boundary station for the adjacent system, Pleasant Bay, where a similar problem existed until the boundary station was moved and sampled only on the flood tide.

The study also performed a temporal analysis of nitrogen levels and the results indicated that there were no significant temporal trends (continuous increases or decreases) within the surface and mid waters of the estuary. This is a useful analysis that is consistent with MEP findings as well. It is also similar to the conclusion of the independent statistical analysis by the Cadmus Group for adjacent Pleasant Bay (October 2011).

Town of Orleans Water Quality Monitoring Program.

The Town of Orleans, while being actively engaged in the study and management of municipal infrastructure and natural resources, committed early on to gathering baseline water quality monitoring data in support of the MEP. Baseline water quality monitoring was undertaken by the Town in the Nauset Marsh, Rock Harbor, Namskaket Marsh and Little Namskaket Marsh systems and in a collaborative manner with the Town of Chatham and the Pleasant Bay Alliance for the Pleasant Bay embayment system shared by Orleans, Harwich and Chatham. For Orleans and the Nauset Harbor/Marsh system (inclusive of Town Cove) specifically, the focus of the effort has been to gather site-specific data on the current nitrogen related water quality to support evaluations of observed water quality and habitat health. Water quality monitoring of the Nauset Harbor System has been a coordinated effort between the Town of Orleans and The Coastal Systems Program at SMAST-UMD.

Concern over declining resource quality of its estuarine systems led the Town of Orleans to initiate the town-wide Orleans Water Quality Monitoring Program in 2001, which continues in a reduced form through present (2011). The 2001 Program was an expansion of a previous effort targeting Pleasant Bay, begun in 1997 by the Orleans Water Quality Task Force. The town-wide monitoring program is focused on restoring and protecting the estuarine habitats associated with the Town of Orleans and is being undertaken in concert with the DEP/SMAST Massachusetts Estuaries Project. This collaborative effort was structured whereby the Town of Orleans provides the support, coordination and oversight of the program through its Planning Office and through its Wastewater Management Steering Committee and SMAST provides the technical and analytical aspects needed for the project through the MEP Technical Team.

The Water Quality Monitoring Program uses primarily trained volunteers for the field data collection efforts. The sampling teams are equipped and trained prior to sampling and given refreshers as needed during the field season. The methods employed are directly comparable to other data collection efforts associated with SMAST, which involve nearly all of the embayments in southeastern Massachusetts, inclusive of Martha's Vineyard and the Island of

Nantucket. Water samples are collected by trained volunteers and town staff for nutrient analysis by the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth. As such, the data can be fully integrated into the MEP technical approach.

The Town of Orleans Water Quality Monitoring Program provided the quantitative water column nitrogen data (2001-2008) required for the implementation of the MEP's Linked Watershed-Embayment Approach (Figure II-1). However, it should be noted that after the first 4 years of monitoring, some stations were discontinued based upon funding concerns and a shift in program emphasis and to make the program more sustainable. Unfortunately, this reduced the segment of the dataset that could be used for model validation, as a full (or nearly full) suite of stations must be consistently sampled to capture the water quality gradients throughout the estuary. Therefore the initial 4 years were the focus for calibration and the 8 year record for the fewer stations were used to determine temporal trends. On this latter point, no consistent temporal trend (increasing or decreasing) was found for total nitrogen, indicating that the Nauset Estuary is currently in balance with its watershed nitrogen loadings. This was also found in a detailed statistical analysis for the adjacent Pleasant Bay System (Cadmas Group 2011). The MEP effort also builds upon previous watershed delineation and land-use analyses, the previous embayment hydrodynamic modeling and historical eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Nauset Estuarine System.

These prior investigations provided significant information related directly to the implementation of the MEP Linked Management Modeling Approach and helped yield insight into the interpretation of the results. In addition, the Town of Orleans' comprehensive Water Quality Monitoring Program was of sufficient rigor to be used as the water quality baseline required for the MEP threshold analysis presented in this MEP Technical Report. The MEP has incorporated appropriate data from previous studies to enhance the determination of nitrogen thresholds for the Nauset Harbor System and to reduce costs to the Town of Orleans.

Regulatory Assessments of Nauset Marsh/Harbor Resources.

In addition to locally generated studies, the Nauset Estuarine System is part of the Commonwealth's environmental surveys to support regulatory needs. The Nauset Estuary contains a variety of natural resources of value to the citizens of Orleans, Eastham and Brewster as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP also gathers the available information on these resources as part of its assessment and presents some of them here for reference by those providing stewardship for this estuary and some in Section VII to support the nitrogen thresholds analysis. For the Nauset Estuary these include:

- Designated Shellfish Growing Area – MassDMF (Figure II-2a,b,c,d)
- Shellfish Suitability Areas – MassDMF (Figure II-3)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-4)
- Mouth of River designation - MassDEP (Figure II-5a,b,c,d)

The MEP effort builds upon earlier watershed delineation and land-use analyses, the hydrodynamic modeling, historical eelgrass surveys and water quality surveys discussed above. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Nauset Marsh/Harbor Estuarine

System. The MEP has incorporated appropriate data from pertinent previous studies to enhance the determination of nitrogen thresholds for the Nauset System and to reduce costs to the Towns of Orleans and Eastham.

Figure II-1. Town of Orleans Water Quality Monitoring Program in Nauset Marsh. Estuarine water quality monitoring stations sampled by the Town and volunteers.

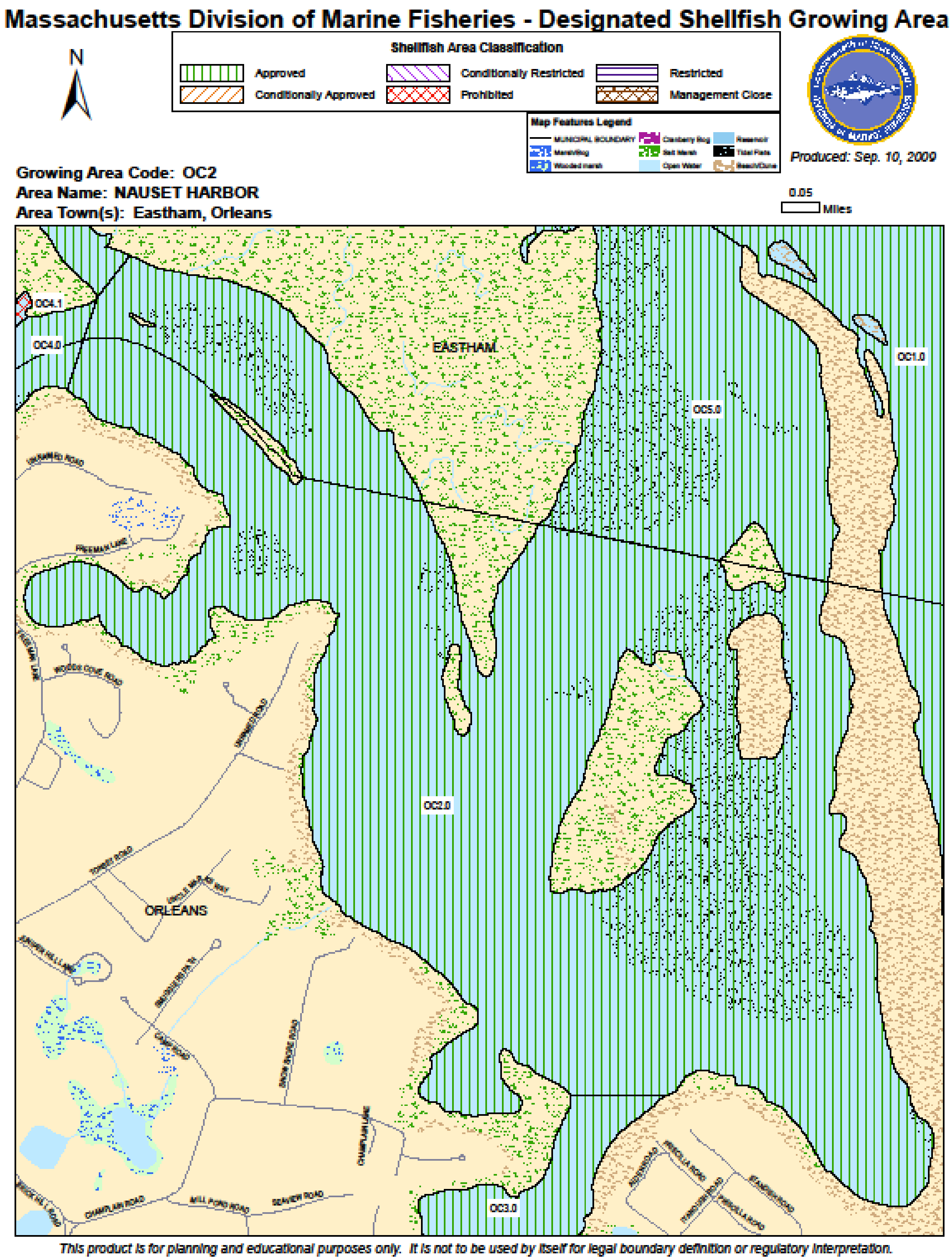


Figure II-2a. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

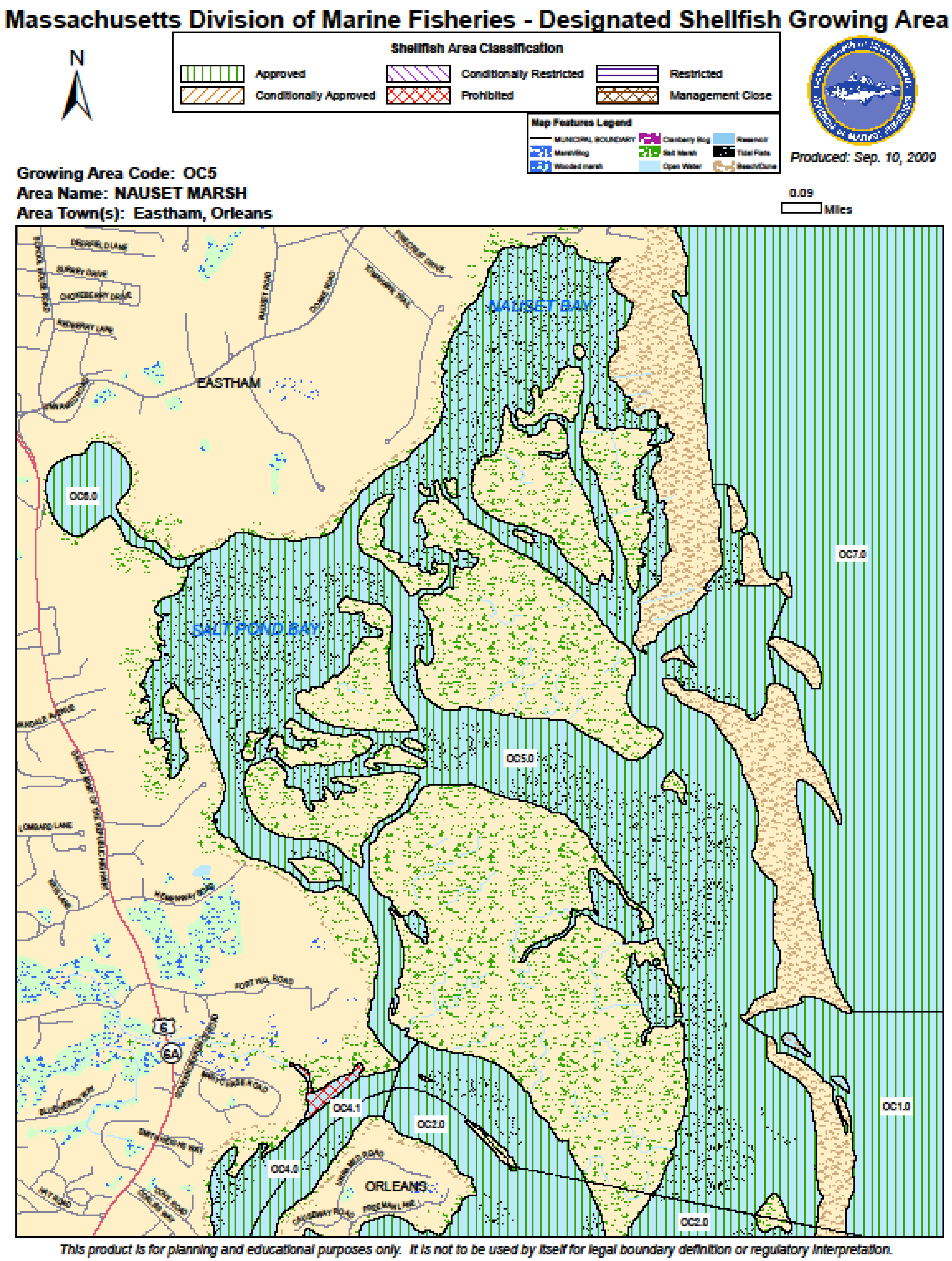


Figure II-2b. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

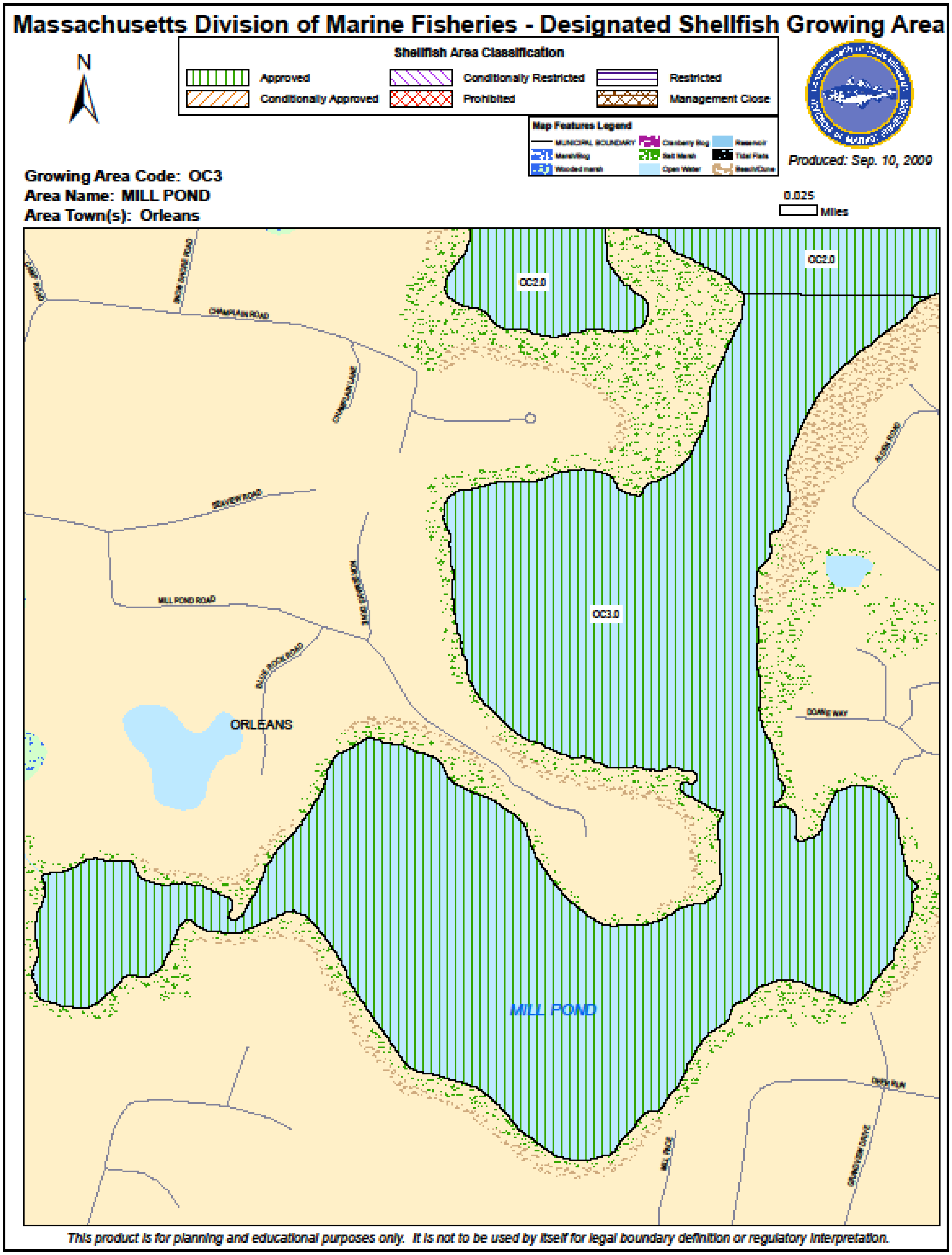


Figure II-2c. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

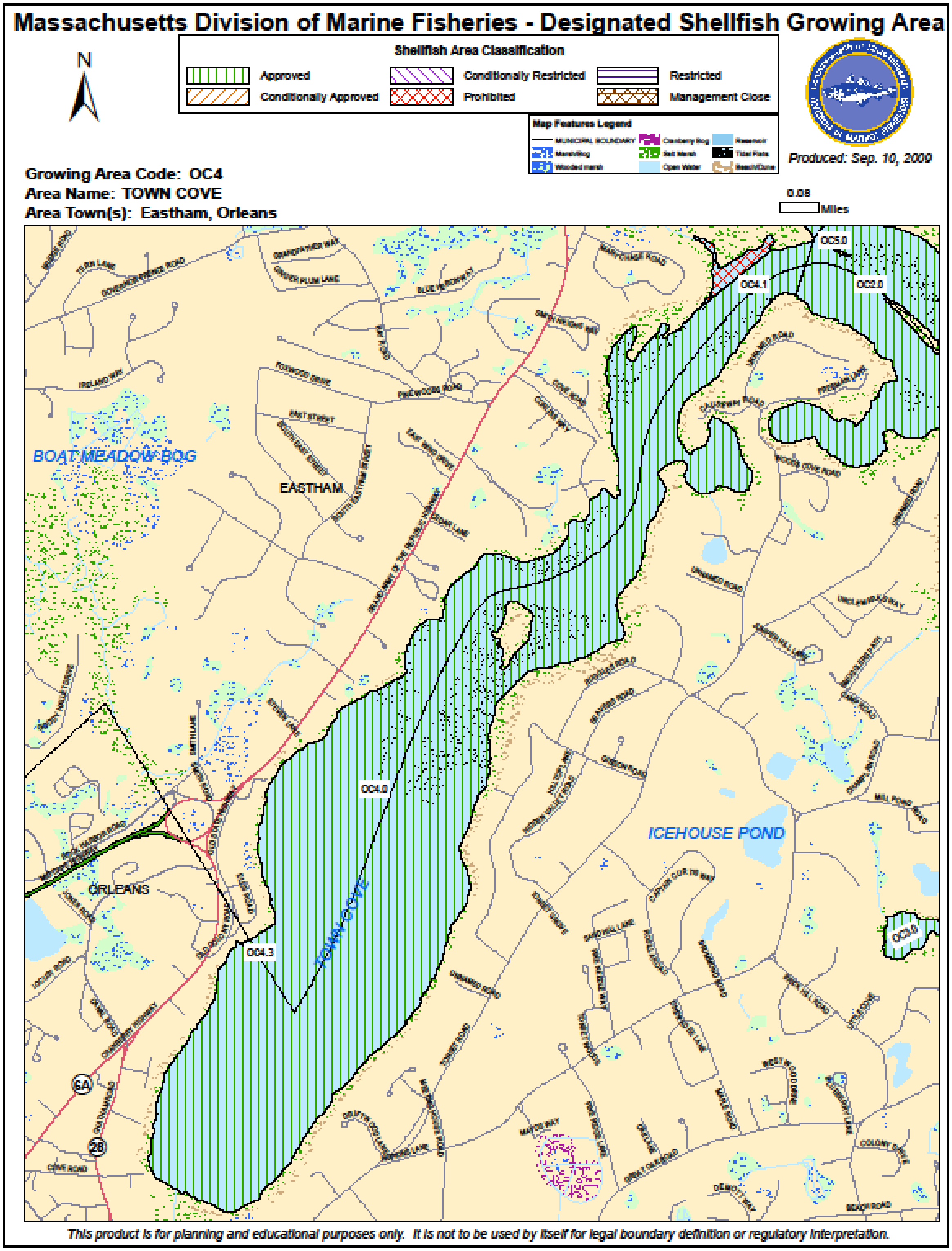


Figure II-2d. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

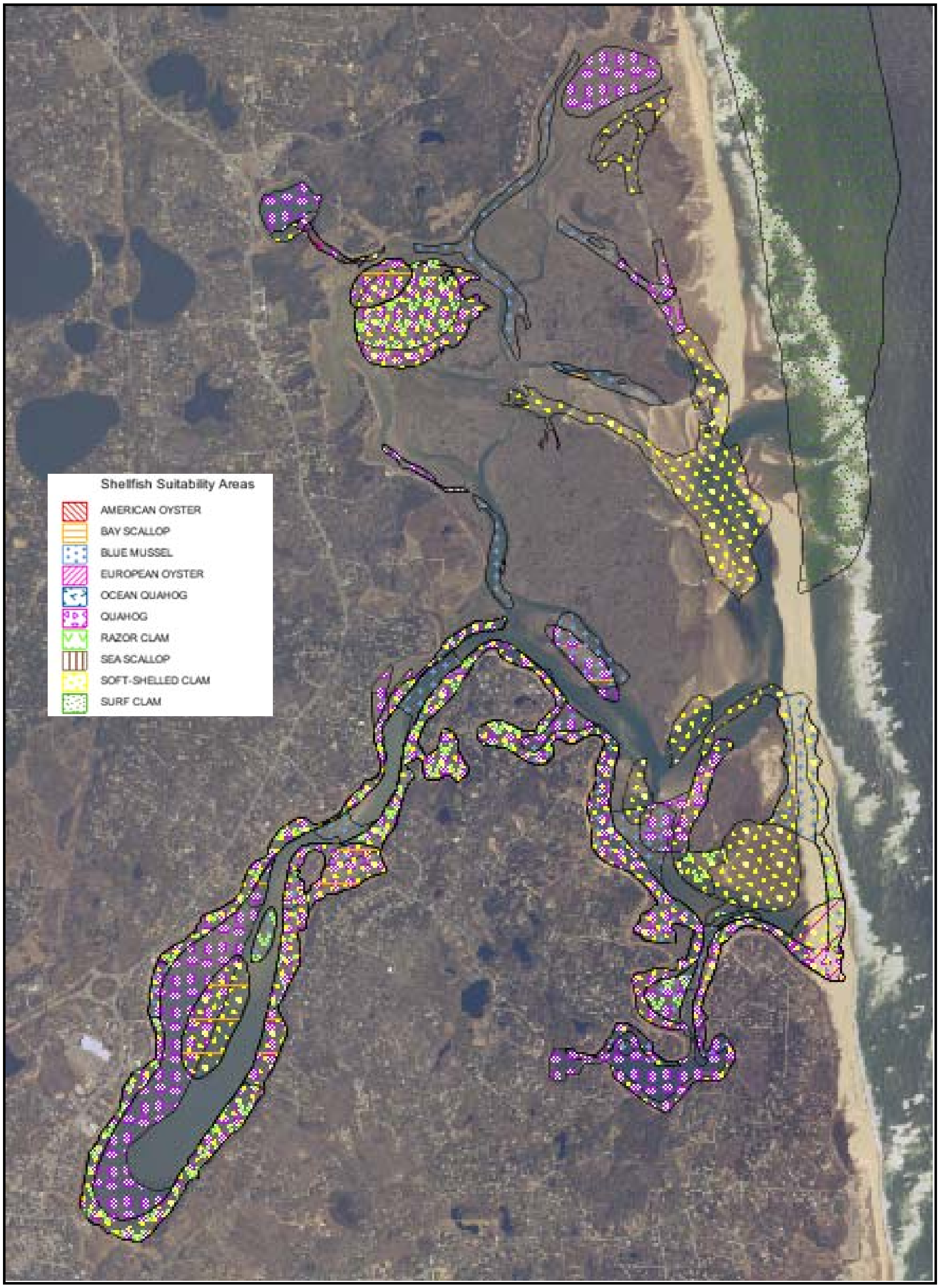


Figure II-3. Location of shellfish suitability areas within the Nauset Marsh/Harbor Estuary System as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

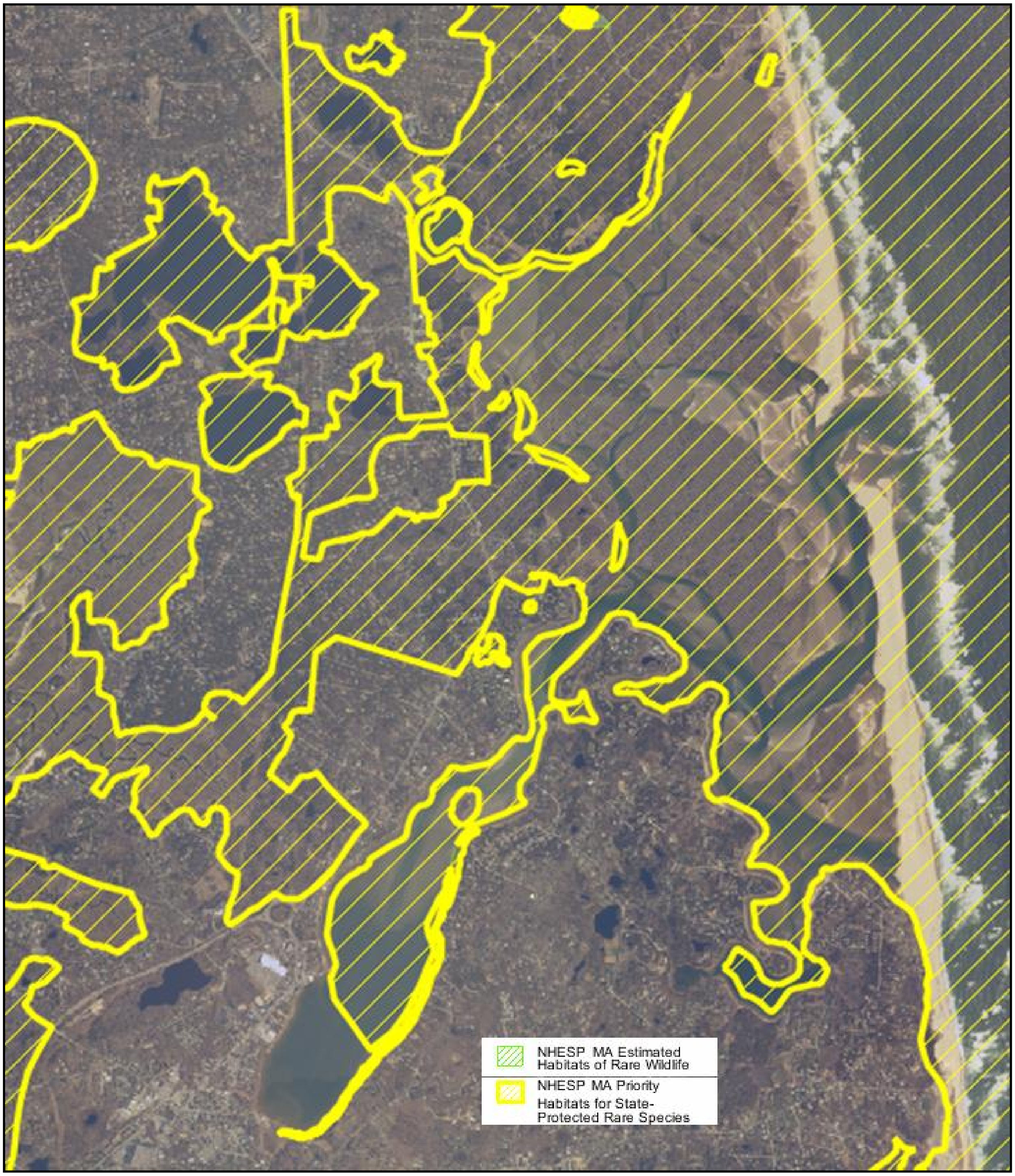


Figure II-4. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Nauset Marsh/Harbor Estuary as determined by - NHESP.

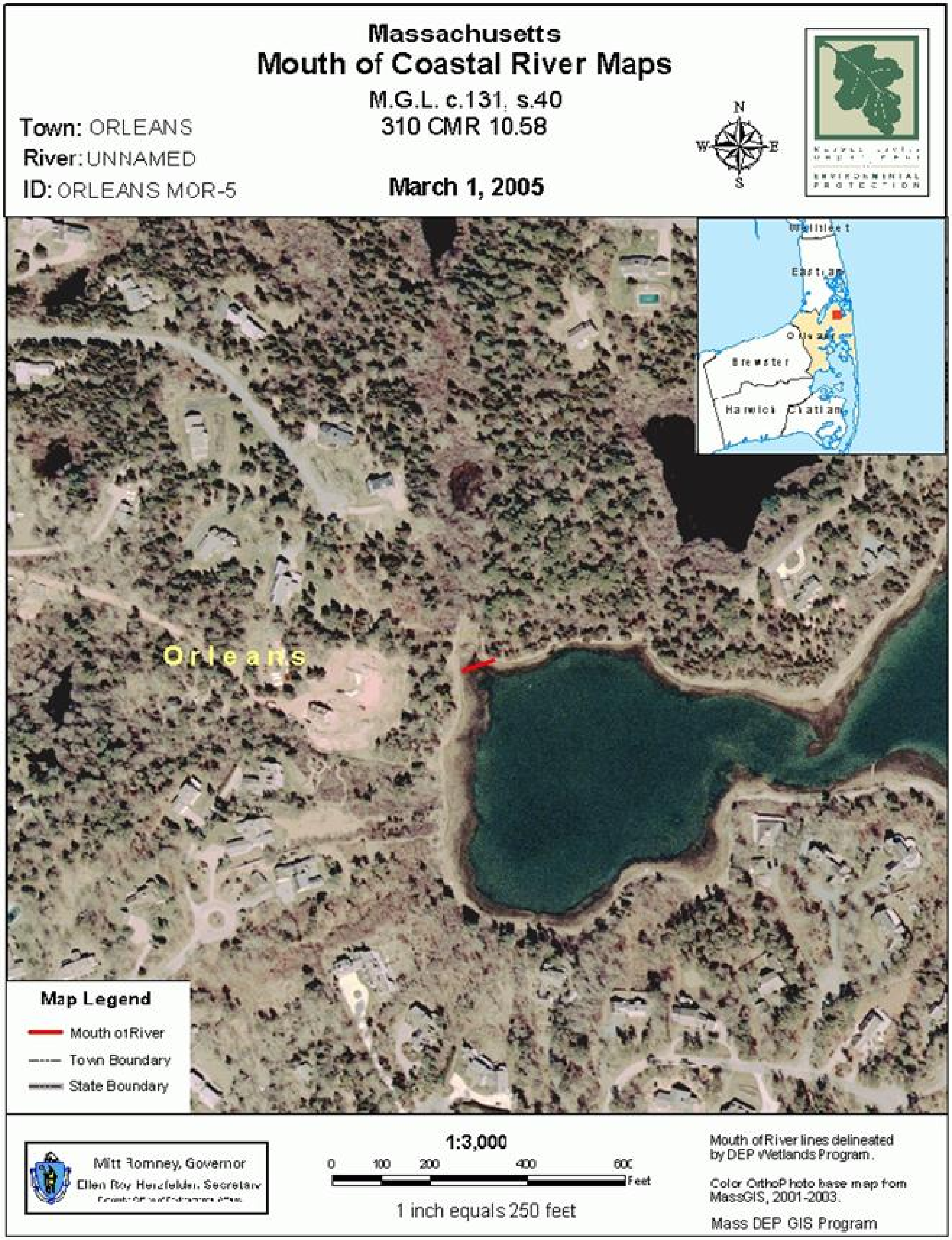


Figure II-5a. Regulatory designation of the mouth of an unnamed coastal river in the Nauset Marsh system under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

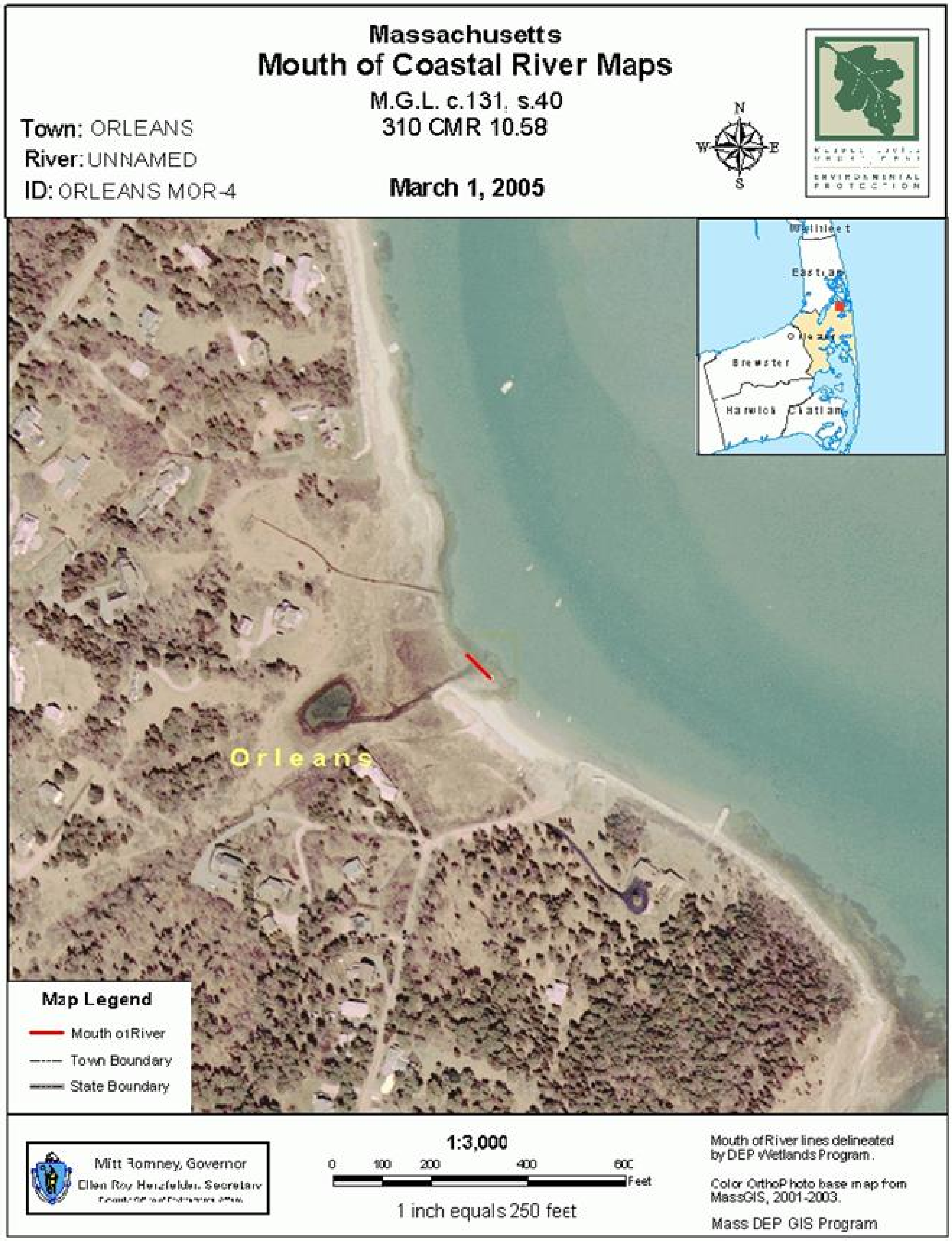


Figure II-5b. Regulatory designation of the mouth of an unnamed coastal river in the Nauset Marsh system under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act

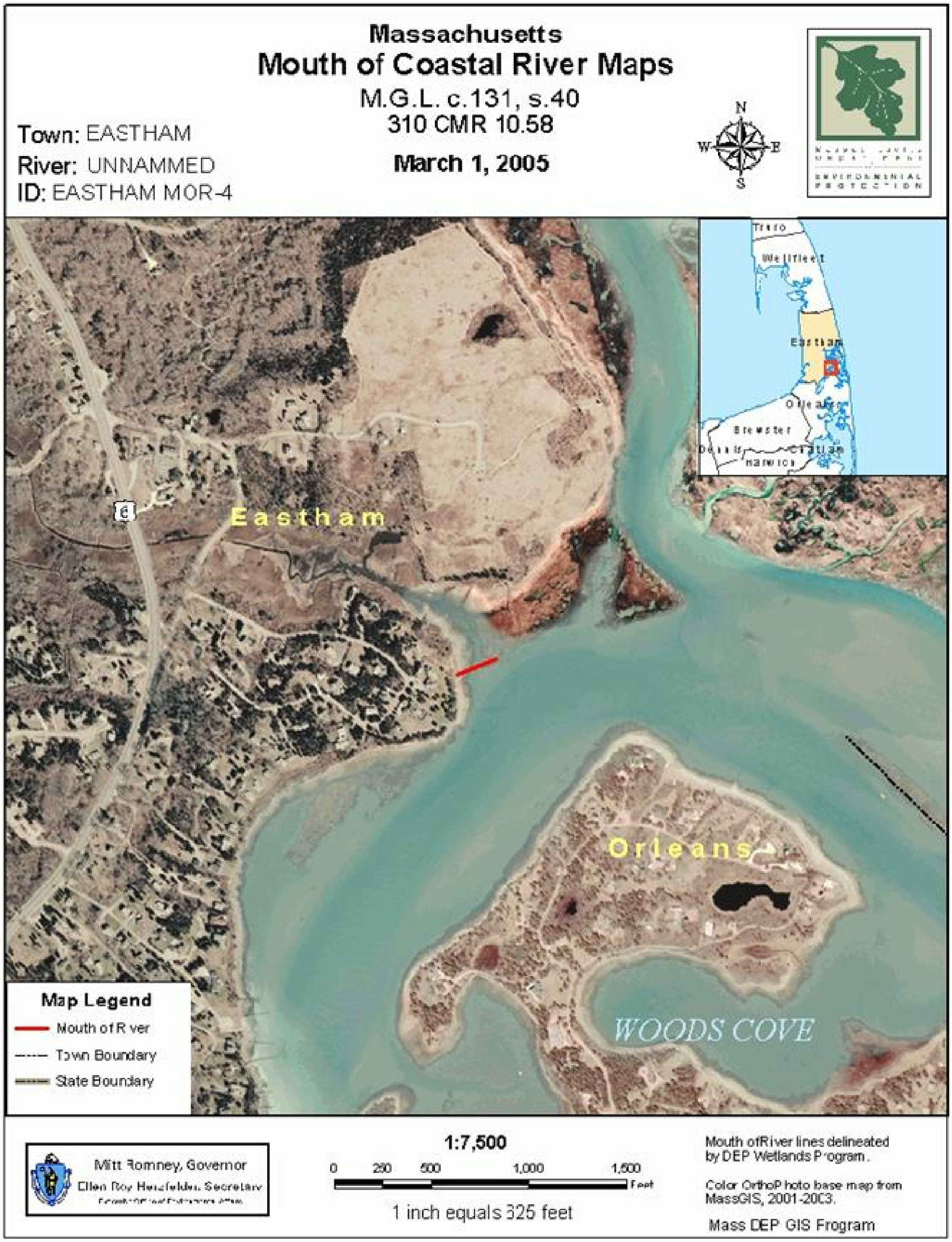


Figure II-5c. Regulatory designation of the mouth of an unnamed coastal river in the Nauset Marsh system under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act

Figure II-5d. Regulatory designation of the mouth of an unnamed coastal river in the Nauset Marsh system under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). The USGS groundwater modelers were central to the development of the groundwater modeling approach used by the Estuaries Project. The USGS has a long history of developing regional models for the six-groundwater flow cells on Cape Cod. Through the years, advances in computing, lithologic information from well installations, water level monitoring, stream flow measurements, and reconstruction of glacial history have allowed the USGS to update and refine the groundwater models. The models developed and utilized by the USGS to organize and analyze the available data use up-to-date mathematical codes and create better tools to answer the wide variety of questions related to watershed delineation, surface water/groundwater interaction, groundwater travel time, and drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including Nauset Estuarine System. This estuary is situated along the eastern edge of the upper portion of Cape Cod and is bounded by the Atlantic Ocean. The Nauset Estuary watershed includes portions of the Towns of Orleans, Eastham, and Brewster.

In the present investigation, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or land area contributing freshwater to the Nauset Marsh estuary system under evaluation by the MEP Project Team. The Nauset Estuarine System is situated at the margin of two groundwater lenses: the Monomoy Lens and the Nauset Lens. These lenses are modeled separately: Nauset in Masterson (2004) and Monomoy in Walter and Whealan (2005). The estuary generally receives watershed discharge via groundwater seepage with only a few small freshwater streams discharging directly into the system. Further modeling of the Nauset Estuary watershed was undertaken to sub-divide the overall watershed into functional sub-units based upon: (a) defining inputs from contributing areas to each major component basin comprising the Nauset Estuary and (b) defining contributing areas to major freshwater aquatic systems (lakes, streams, wetlands) that generally attenuate nitrogen passing through them on the way to the estuary. The three-dimensional numerical models employed are also being used to evaluate the contributing areas to public water supply wells in the overall Monomoy groundwater flow cell, although none occur in this watershed. Model calibration of the Nauset Estuary included surface water discharges measured as part of the MEP stream flow program (2003 to 2004) and historic stream gauge information.

The relatively transmissive sand and gravel deposits that comprise most of Cape Cod create a hydrologic environment where 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). Freshwater discharge to estuaries is usually composed of surface water inflow from streams, which receive much of their water from groundwater base flow and direct groundwater discharge. For a given estuary, differentiating between these two water inputs and tracking the sources of nitrogen that they carry requires determination of the portion of the watershed that contributes directly to streams and the portion of the groundwater system that discharges directly into the estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Nauset Estuarine System and its various subwatersheds, such as Salt Pond, Town Cove, and Minister Pond, were delineated using regional groundwater models of the Monomoy Lens flow cell (Walter and Whealan, 2005) and the Nauset Lens flow cell (Masterson, 2004). The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, *et al*., 2000) was used to simulate groundwater flow in the Monomoy Lens, while the USGS variable density groundwater model SEAWAT (Guo and Langevin, 2002) was used in the Nauset Lens. SEAWAT was used in the Nauset Lens because most of the outer Cape freshwater groundwater lens floats on salt water rather than having bedrock at the base like most of the Monomoy Lens area. The USGS particle-tracking program MODPATH4 (Pollock, 2000), which uses output files from both MODFLOW-2000 and SEAWAT to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal basins. This approach was used to determine the contributing areas to the entire Nauset System and also to determine portions of recharged water that may flow through freshwater ponds and streams prior to discharging into the estuary's component basins.

The Monomoy Flow Model grid consists of 164 rows, 220 columns and 20 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top 17 layers of the model extend to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft (Walter and Whealan, 2005). The top of layer 8 resides at NGVD 29 with layers 1-7 stacked above and layers 8-20 below. Since water elevations are less than +40 ft in the portion of the Monomoy Lens in which the portions of the Nauset Marsh estuary watershed reside, the three uppermost layers of the model are inactive. Layer 18 has a thickness of 40 feet and extends to 140 feet below NGVD 29, while layer 19 extends to 240 feet below NGVD 29. The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics (up to 525 feet below NGVD 29); since bedrock is approximately 400 feet below NGVD 29 in most of the Monomoy Lens portion of the Nauset Marsh area, the two lowest model layers were active in this area of the model. The rewetting capabilities of MODFLOW-2000, which allows drying and rewetting of model cells, were used to simulate the top of the water table, which varies in elevation depending on the location in the flow cell.

The Nauset Flow Model is part of a groundwater model that extends across all four groundwater lens of the outer Cape. The model grid consists of 320 rows, 110 columns and 23 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top layer extends to 5 feet below NGVD 29, the second layer extends to 20 feet below NGVD 29, and then layers are uniformly 20 feet thick down to 200 ft below NGVD 29. Below this level, layers are uniformly 25 ft thick with the bottom layer (#23) extending to 500 feet below NGVD 29, which is specified as a no-flow boundary in the model and is generally the top of the bedrock surface beneath the outer Cape (Masterson, 2004). SEAWAT allows the transient modeling of the freshwater/saltwater interface, which is generally important for defining groundwater discharge along the coast and specifically important for modeling potential impacts of municipal drinking water well withdrawals. The system was calibrated using precipitation and pumping conditions recorded from 1930 to 2002.

The two groundwater lenses that are part of the Nauset Marsh watershed are derived from two different sources of glacial sediments. The section of the Monomoy Lens occupied by the watershed is the Harwich Outwash Plain Deposits (Oldale, 1974). These deposits generally show a fining downward sequence with sand and gravel deposits deposited in glaciofluvial (river) and near-shore glaciolacustrine (lake) environments underlain by fine sand, silt and clay deposited in deeper, lower-energy glaciolacustrine environments. Most groundwater flow in the aquifer occurs in shallower portions of the aquifer dominated by coarser-grained sand and gravel deposits (Oldale, *et al*., 1971). The Nauset Lens portion of the watershed to the Nauset Estuarine System is predominantly Eastham Plains Deposits (Masterson, 2004). The Eastham Plains Deposits are the youngest of the outer Cape glacial deposits (Oldale, 1992) and were the furthest from the sediment source (*i.e.*, the glacier face). As such, these deposits tend to be composed of finer sands and are underlain by silts and clays.

Modeling and field measurements of contaminant transport at the Massachusetts Military Reservation have shown that deposited materials similar to those in both lens are highly permeable (*e.g*., Masterson, *et al*., 1996). Given their high permeability, direct rainwater run-off is typically rather low for this type of watershed system. Lithologic data used to determine hydraulic conductivities used in the groundwater models were obtained from a variety of sources including well logs from the USGS, local Town records and data from previous investigations. Final aquifer parameters were determined through calibration to observed water levels and stream flows as appropriate. Hydrologic data used for Monomoy Lens model calibration included historic water-level data obtained from USGS records and local Town and stream flow data collected in 1989-1990 as well as 2003. Hydrologic data used for Outer Cape model calibration included historic water-level data obtained from USGS records for the long-term monitoring network and three synoptic water table surveys in November 1975, June 2001, and May 2002.

The Monomoy Flow Cell groundwater model simulates steady state, or long-term average, hydrologic conditions including a long-term average recharge rate of 27.25 inches/year and the pumping of public-supply wells at average annual withdrawal rates for the period 1995-2000 with a 15% consumptive loss. Large withdrawals of groundwater from pumping wells may have a significant influence on water tables and watershed boundaries and therefore the flow and distribution of nitrogen within the aquifer. After accounting for the consumptive loss, water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within designated residential areas utilizing on-site septic systems. In the Outer Cape groundwater model, an average recharge rate of 24 inches/year was used. Since drinking water is pumped by private wells and remaining water after consumptive use is recharged through on-site septic systems on the same site as the private wells, no adjustments to recharge were made in the Nauset Lens portion of the Outer Cape groundwater model. These recharge rates are based on the most recent USGS information.

III.3 NAUSET MARSH ESTUARY CONTRIBUTORY AREAS

The refined watershed and sub-watershed boundaries for the Nauset Marsh embayment system, including Town Cove, Salt Pond, and Ministers Pond and other sub-estuaries (Figure III-1) were determined by the United States Geological Survey (USGS). Model outputs of watershed boundaries were “smoothed” to (a) correct for the grid spacing, (b) to enhance the accuracy of the characterization of the pond and coastal shorelines, (c) to include water table data in the lower regions of the watersheds near the coast (as available), (d) to more closely match the estuarine component basins of the tidal hydrodynamic model, and (e) to address streamflow measurements collected as part of the MEP. The smoothing refinement was a collaborative effort between the USGS and the rest of the MEP Technical Team. Overall, 13 sub-watershed areas plus a portion of the flow from Bakers Pond were delineated within the Nauset Estuary study area.

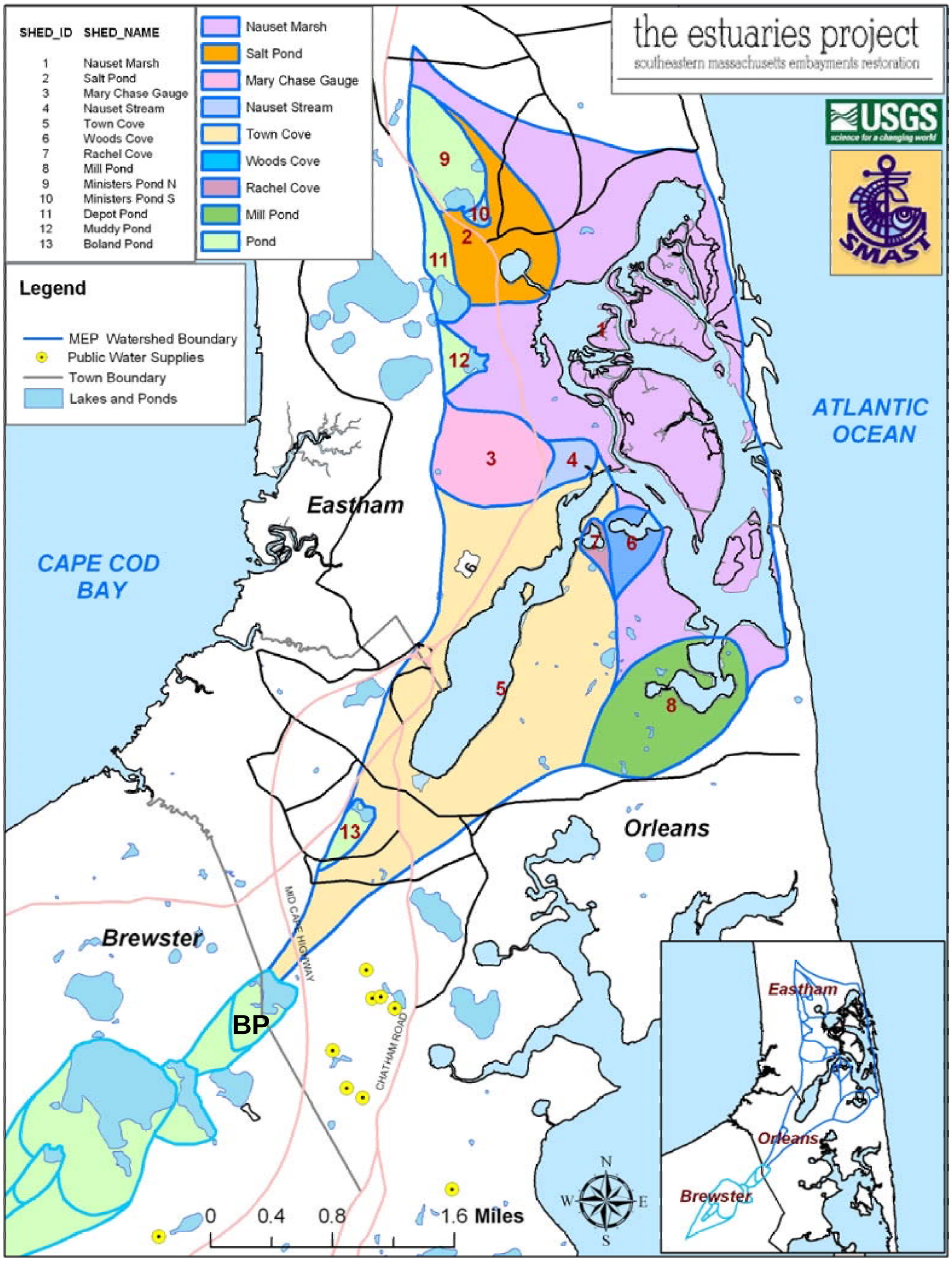


Figure III-1. Watershed delineation for Nauset Estuarine System. Subwatershed delineations are based on USGS groundwater model output with modifications to better address pond and estuary shorelines and MEP stream gauge measurements. Sub-watersheds within the estuary portion of the watershed (e.g., Town Cove) were selected based upon the component basins comprising the Nauset Estuary in the water quality model (see Section VI). Baker Pond ("BP" in the above figure) is shared with the Pleasant Bay MEP watershed (Howes, et al., 2006) and discharges a portion of its watershed outflow into the Town Cove subwatershed of the overall Nauset Marsh watershed.

Table III-1 provides the daily freshwater discharge volumes for each of the subwatersheds as calculated by the groundwater model and these volumes were used to assist in the salinity calibration of the tidal hydrodynamic models and to determine hydrologic turnover in the lakes/ponds, as well as for comparison to directly measured surface water discharges. The overall estimated freshwater inflow into the Nauset Marsh estuary from its MEP watersheds is 34,790 m3/d.

Table III-1. Daily average groundwater discharge from each of the sub-watersheds comprising the watershed to the Nauset Estuary, as determined from the two regional USGS groundwater models used for the watershed delineation.

Watershed	#	Watershed Area (acres)	Discharge	
			m^3/day	ft^3/day
Nauset Marsh	1	1,860	12,927	456,509
Salt Pond	2	298	2,014	71,119
Mary Chase Rd Gauge	3	265	1,791	63,242
Nauset Stream	4	53	358	12,640
Town Cove	5	1,486	11,007	388,696
Wood Cove	6	72	556	19,646
Rachel Cove	7	19	147	5,207
Mill Pond	8	342	2,627	92,755
Minister Pond (N)	9	177	1,197	42,273
Minister Pond (S)	10	12	84	2,966
Depot Pond	11	94	637	22,508
Muddy Pond	12	51	346	12,223
Boland Pond	13	44	341	12,052
Baker Pond	BP	99	757	26,749
NAUSET ESTUARY TOTAL			34,790	1,228,585

Notes: 1) discharge volumes are based on 27.25 inches of annual recharge over the Monomoy Lens portion of the watershed (*i.e.*, Orleans and Brewster) and 24 in/yr of recharge over the Nauset Lens portion of the watershed (*i.e.*, Eastham); 2) these flows do not include precipitation on the surface of the estuary; 3) upgradient ponds often discharge to numerous downgradient subwatersheds, percentage of outflow is determined by length of downgradient shoreline going to each subwatershed; these corrections are included in the total system recharge; 4) Baker Pond is shared with the Pleasant Bay MEP watershed (Howes, *et al*., 2006) and the indicated area and flow is the portion that contributes to the Nauset Marsh watershed; 5) totals may not match due to rounding; 6) Minister Pond (S) also known as Schoolhouse Pond

The MEP watershed delineation is the second watershed delineation completed in recent years for the Nauset Marsh System. Figure III-2 compares the delineation completed under the current effort with the delineation completed by the Cape Cod Commission as part of the Coastal Embayment Project (Eichner, *et al*., 1998). The CCC delineation was developed based on regional water table measurements collected from available well data over a number of years and normalized to average conditions. This analysis included water table data collected in Johnson and Davis (1988). The Commission's delineation was incorporated into the Commission's regulations through the three versions of the Regional Policy Plan (CCC, 1996, 2001, and 2009).

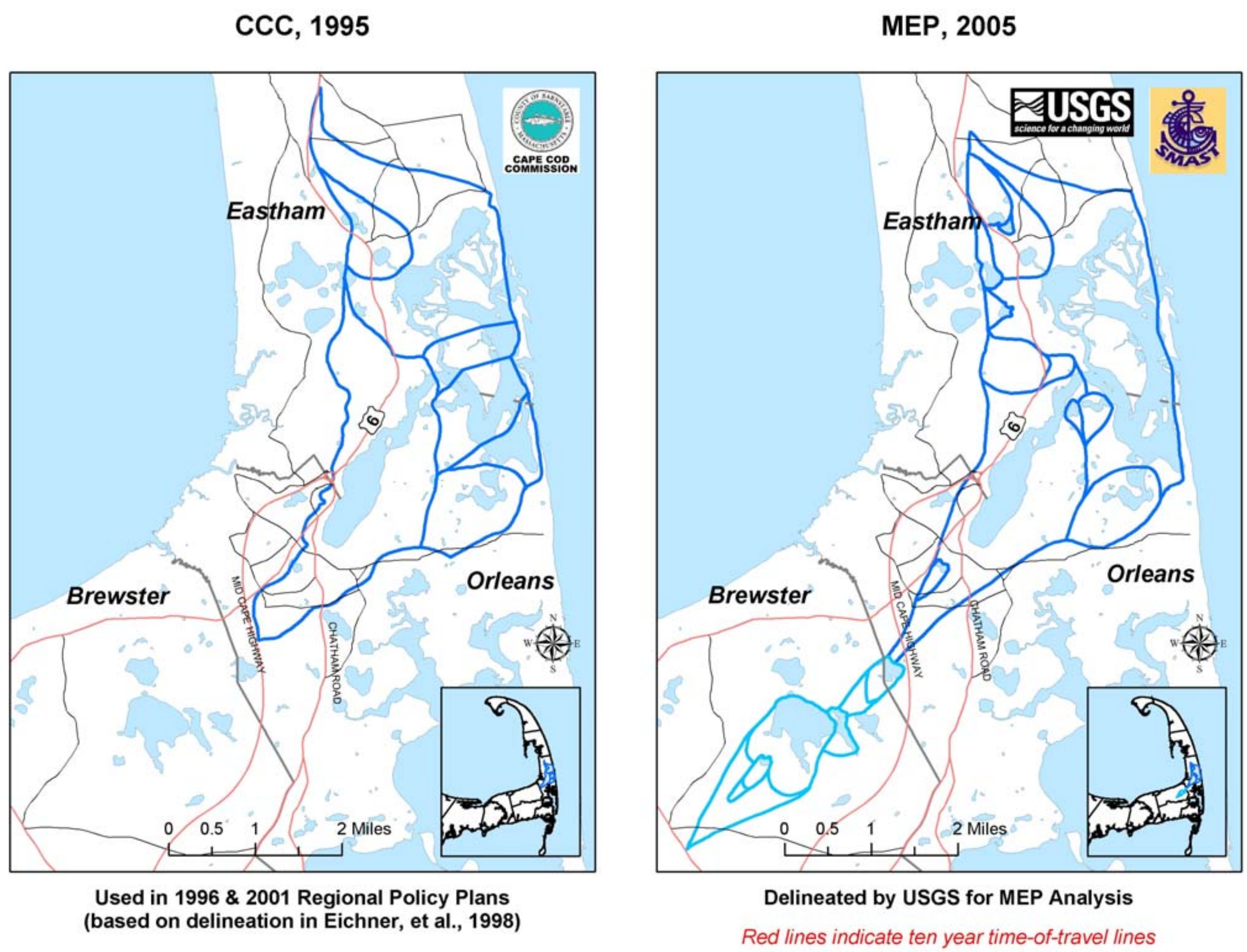


Figure III-2. Comparison of MEP watershed and subwatershed delineations for the Nauset Estuary used in the current assessment and the Cape Cod Commission delineation (Eichner, *et al.*, 1998), which has been used in three Barnstable County Regional Policy Plans (CCC, 1996, 2001, and 2009). The MEP watershed area for the Nauset System as a whole is only 1% smaller than 1998 CCC delineation.

The MEP watershed area for the Nauset Marsh system as a whole is roughly the same area as the 1998 CCC delineation (6,361 acres vs. 6,425 acres, respectively). The areas that are included in the delineations are slightly different, largely due to the internal sub-watershed refinements included in the MEP delineations and the change in the location of the regional groundwater divide in the Nauset Lens. For example, the MEP delineation refinements include a portion of flow from Bakers Pond, which is shared with the Pleasant Bay watershed (Howes, *et al.*, 2006), which expands the Town Cove sub-watershed into Nickerson Park in Brewster. The MEP watershed delineation also includes interior sub-watersheds to various components of the Nauset Marsh system, such as ponds that were not fully included in the CCC delineation, as well as sub-watersheds to the stream gauged during the MEP: near Mary Chase Road (Section IV.2). These refinements are another benefit of the update of the USGS regional groundwater models.

The evolution of the watershed delineation for the Nauset Estuarine System has allowed increasing accuracy as each new version adds new hydrologic data to that previously collected; the groundwater model allows all this data to be organized and to be brought into congruence with data from adjacent watersheds. The evaluation of older data and incorporation of new data during the development of the model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model and strengthens the MEP analysis and the use of this model 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 down gradient estuary. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the aquatic systems and ultimately to the receiving waters of the Nauset Estuarine System (Section VI).

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

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

In order to determine watershed nitrogen loading inputs to the Nauset Estuary System, the MEP Technical Team developed nitrogen-loading rates (Section IV.1) to each component basin of the estuary and its watershed (Section III). The Nauset Estuary watersheds were sub-divided to define contributing areas to each of the major inland freshwater systems and to each major component basin comprising the estuary. A total of 13 sub-watershed areas plus a portion of the flow from Bakers Pond were delineated within the Nauset Estuary study area including watersheds to the following ponds: Ministers (N), Ministers (S) {a.k.a. Schoolhouse}, Depot, Muddy, and Boland Ponds. Bakers Pond is shared with the Pleasant Bay MEP watershed (Howes, *et al.*, 2006) and receives recharge flows and nitrogen loads from Cliff, Little Cliff, and Ruth Ponds. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and each portion of the estuary (see Section III).

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the estuary. Typically, this includes review of watershed areas less than 10 years groundwater travel time to the estuary, as determined by the USGS watershed model. In this watershed, project staff also reviewed the age of single-family residences in each of the watersheds. This review found that the average age of single-family residences in each of the sub-watersheds ranged from 35 to 74 years old. Given that the development pattern within most of the watersheds is either fairly evenly spread over the whole sub-watershed or concentrated close to the estuary shoreline, these ages suggest that most of the present nitrogen loads have impinged upon the estuary. Therefore it appears that the present nitrogen sources within the watersheds accurately represent nitrogen loading to the estuarine waters (after accounting for natural attenuation, see below) and that the distinction between time of travel in the sub-watersheds is not required for modeling existing versus build-out conditions. This finding is further reinforced by the small changes in land use that have occurred in the four years since the Nauset Marsh watershed land use was originally reviewed (see buildout discussion). Overall, based on the review of all this information, it was determined that the Nauset Estuary is currently in balance with its watershed load.

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 site-specific studies is applied to other portions. The Linked Watershed-Embayment Management Modeling Approach (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon sub-watershed-specific land uses and pre-determined nitrogen loading rates based on regional analyses. For the Nauset Estuarine System, the model uses land-use data from the Towns of Orleans, Eastham, and Brewster that is transformed to nitrogen loads using both regional nitrogen loading factors and local watershed-specific data (such as parcel-by-parcel water use and alternative septic system monitoring). 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 basin, since attenuation during transport is included at a later stage.

Natural attenuation of nitrogen during transport from land-to-sea (Section IV.2) within the Nauset Estuary watershed was determined based upon a site-specific study of streamflow and assumed and measured attenuation in the up-gradient freshwater ponds. Streamflow and associated nitrogen load was characterized at the discharge of a small stream, from an up-gradient wetland, passing under Mary Chase Road. A sub-watershed to this stream discharge point allowed comparison between field collected data from the stream and the estimate from the nitrogen-loading sub-model. Nitrogen attenuation in individual ponds is generally estimated based on available information. Attenuation through the ponds is conservatively assumed to equal 50% (based upon prior MEP studies), unless available monitoring and pond physical data is reliable enough to calculate a pond-specific nitrogen attenuation factor. Streamflow and associated surface water attenuation is included in the MEP 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. In the present effort, six freshwater ponds have delineated sub-watersheds within the in the Nauset Estuary watershed. If smaller aquatic features that have not been included in this MEP analysis were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly overestimated given the distribution of nitrogen sources within the watershed.

Based upon the evaluation of the watershed, the MEP Technical Team used the watershed Nitrogen Loading Model to estimate nitrogen loads for the sub-watersheds that directly discharge groundwater to the estuary without flowing through one of the interim pond and stream measuring points. Internal nitrogen recycling was also determined throughout the tidal reaches of the Nauset Estuarine System; measurements were made to capture the spatial distribution of nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management period and the focus 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

Since the watershed to the Nauset Estuary includes portions of the Towns of Orleans, Eastham, and Brewster, Estuaries Project staff obtained digital parcel and tax assessor's data from each town to serve as a base for the watershed nitrogen loading model. Digital parcels and land use/assessors data for Orleans and Eastham are from 2007, while Brewster data are from 2004. Brewster data relies on information collected during the Pleasant Bay MEP assessment (Howes, *et al*., 2006). These land use databases contain traditional information regarding land use classifications (MassDOR, 2009) plus additional information developed by the towns. This effort was completed with the assistance from GIS staff from the Cape Cod Commission (CCC).

Figure IV-1 shows the land uses within the Nauset Estuary watershed. Land uses in the study area are grouped into seven (7) land use categories: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) recreational (campground), 6) undeveloped, and 7) public service/government, including road rights-of-way. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MassDOR, 2009). "Public service" in the MassDOR system is tax-exempt properties, including lands owned by government (*e.g.*, wellfields, schools, open space, roads) and private non-profit groups like churches and colleges.

Two land use categories, residential and public service, are equally dominant in the overall Nauset Estuary watershed. Residential land uses are 43% of the watershed area, while public service (mostly comprised of the Cape Cod National Seashore) is 42% of the watershed area (Figure IV-2). The third largest area (8%) is undeveloped properties. Residential land uses are the dominant land use in each of the contributing sub-watersheds except for the Nauset Marsh sub-watershed, where public service is 57% of the watershed area. Residential land uses vary from 32% in the Nauset Marsh sub-watershed to 68% in the Woods Cove watershed. Where residential land uses are the dominant type, public service land (mostly owned by the US Government) is the second most dominant land use type, except for the Mill Pond sub-watershed where undeveloped lands are the second most dominant (21% of the watershed area).

In all the sub-watershed groupings shown in Figure IV-2, residential parcels are the dominant parcel type, ranging between 72% and 87% of all parcels in the sub-watersheds and 75% of all parcels in the Nauset Marsh system watershed. Undeveloped parcels are generally the second most frequent in the sub-watershed, which is likely indicative of more isolated undeveloped small parcels than large undeveloped parcels that can be subdivided. Single-family residences (MassDOR land use code 101) are 88% to 95% of residential parcels in these sub-watershed groupings and 91% of the residential parcels throughout the Nauset Estuary System watershed.

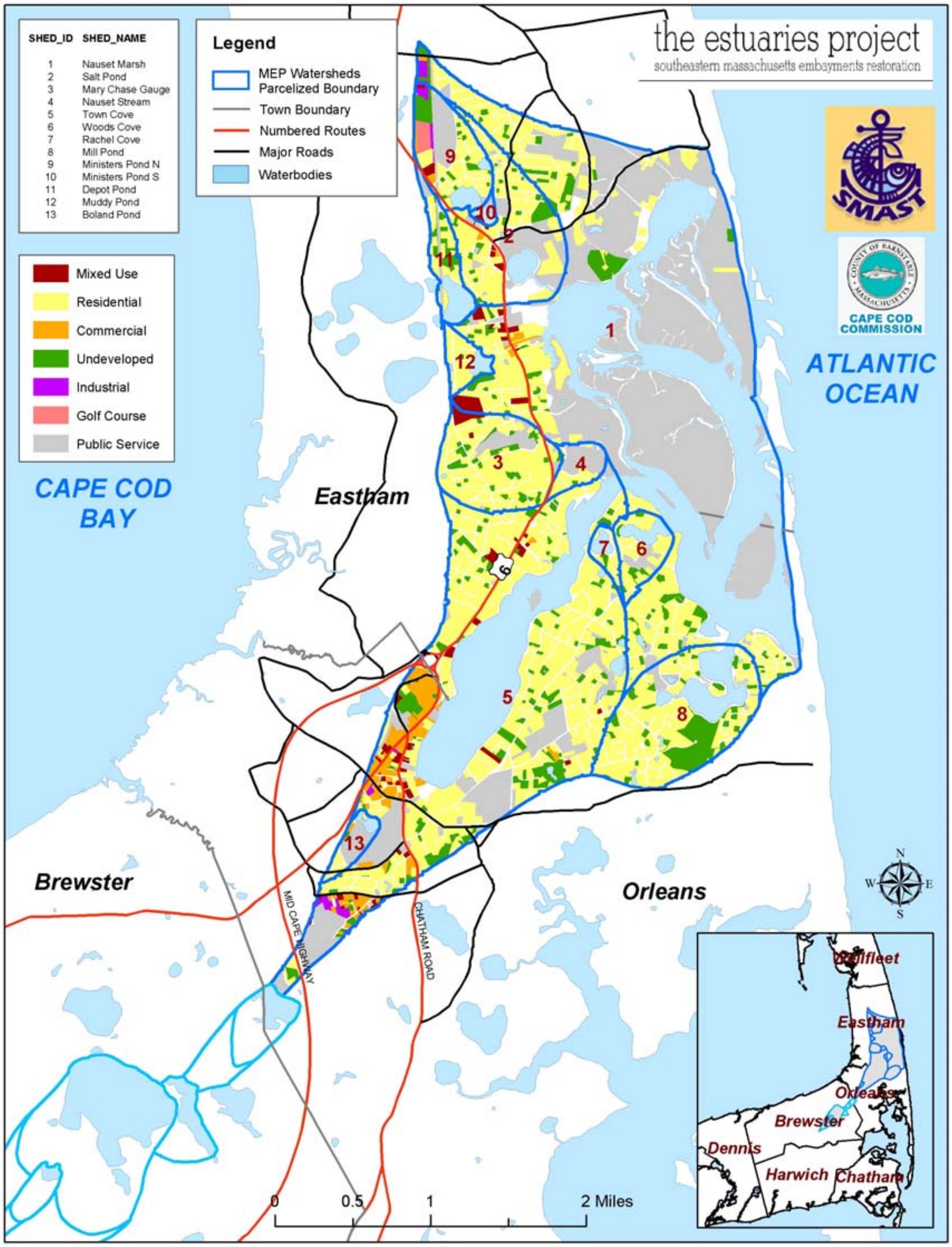


Figure IV-1. Land-use in the Nauset Estuary watershed and sub-watersheds. The system watershed extends over portions of the Towns of Orleans, Eastham, and Brewster. Land use classifications are based on respective town assessor classifications and MADOR (2009) categories. Base assessor and parcel data for Orleans and Eastham is from 2007, while Brewster data is from 2004.

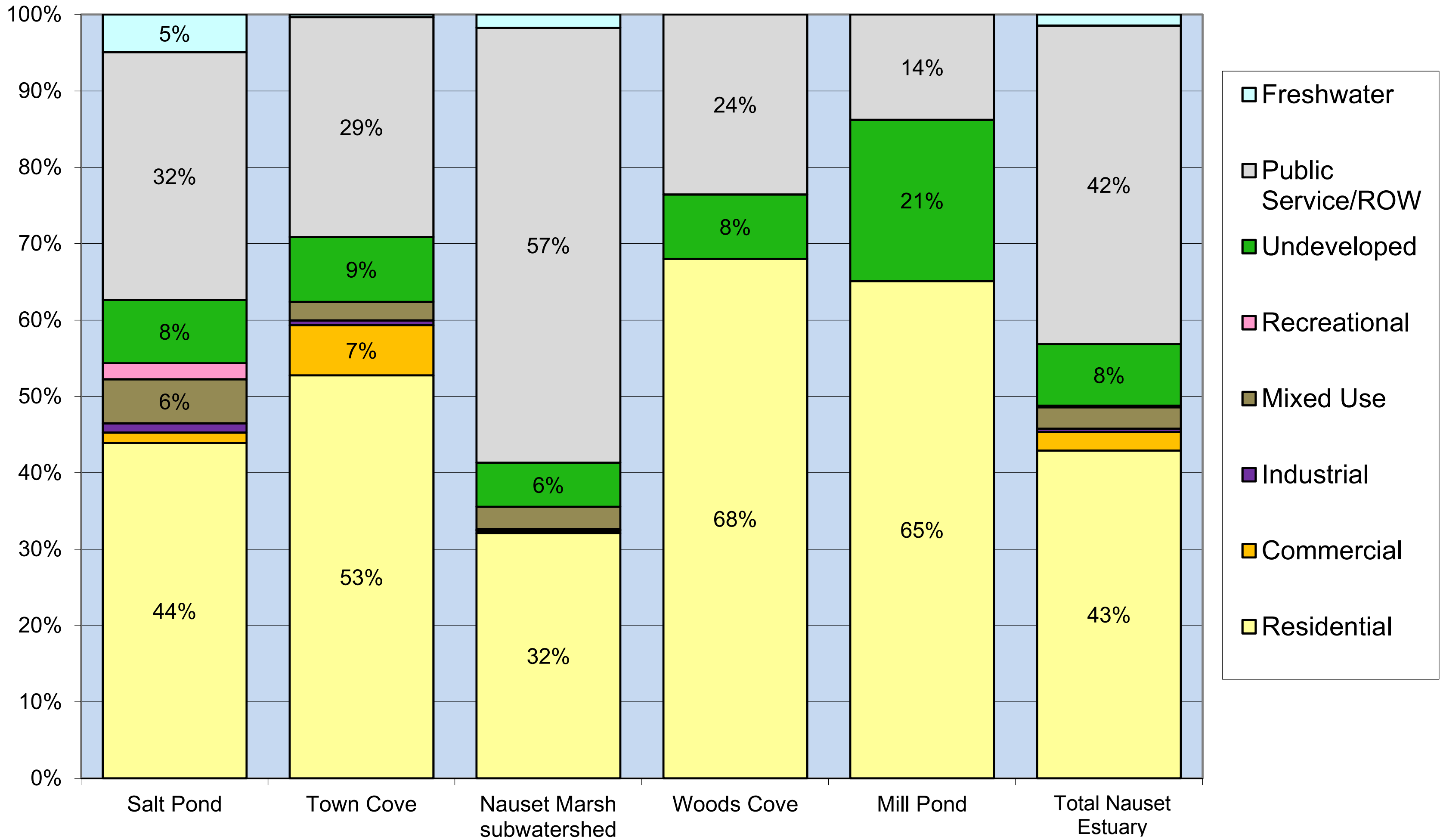


Figure IV-2. Distribution of land-uses by area within the Nauset Estuary watershed and five component sub-watersheds. Land use categories are based on town assessors' land use classifications and groupings recommended by MADOR (2009). Only percentages greater than or equal to 5% are shown.

In order to estimate wastewater flows within the Nauset Estuary study area, MEP staff also obtained parcel-by-parcel water use data from the two towns in the watershed with public water supply (Orleans and Brewster); the Town of Eastham relies on private, on-site wells for drinking water. The Orleans water data represents twelve months of water use between 2002 and 2003 and Brewster water data is three years between 2002 and 2004 (personal communication, Paul Hicks, Brewster Water Department Superintendent). The Orleans and Brewster water use datasets are the town-supplied datasets utilized in the Pleasant Bay (Howes, *et al.*, 2005), Little Namskaket (Howes, *et al.*, 2007a), Rock Harbor (Howes, *et al.*, 2007b), and Namskaket (Howes, *et al.*, 2007c) MEP reports. The Orleans dataset also corresponds to part of the same water use period (mid-2002 to mid-2005) that the town is using for their Comprehensive Wastewater Management Plan (CWMP) preparation (Wright-Pierce, 2010). Brewster is utilizing water use from 2009 for their current CWMP efforts (CDM, 2011). The water use data was linked to the respective town parcel databases by the Cape Cod Commission GIS Department staff.

Measured water use is used to estimate wastewater-based nitrogen loading from individual parcels; average water use is used for each parcel with multiple years of data. The final wastewater nitrogen load for each parcel is based upon the measured water-use, wastewater nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2). All parcels are assumed to use on-site septic systems unless additional information is available.

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

The Massachusetts Estuaries Project septic system nitrogen loading rate is fundamentally based upon a per capita nitrogen load to the receiving aquatic system. Specifically, the MEP septic system wastewater nitrogen loading is based upon a number of studies and additional information that directly measured septic system and per capita loads on Cape Cod or in similar geologic settings (Nelson *et al*. 1990, Weiskel & Howes 1991, 1992, Koppelman 1978, Frimpter *et al*. 1990, Brawley *et al*. 2000, Howes and Ramsey 2000, Costa *et al*. 2001). Variation in per capita nitrogen load has been found to be relatively small, with average annual per capita nitrogen loads generally between 1.9 to 2.3 kg person-yr^{-1}.

However, given the seasonal shifts in occupancy and past rapid population growth throughout southeastern Massachusetts, decennial census data yields accurate estimates of total population only in selected watersheds. To correct for this uncertainty and more accurately assess current nitrogen loads, the MEP employs a water-use approach. The water-use approach is applied on a parcel-by-parcel basis within a watershed, where annual water meter data is linked to 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 down gradient 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). Down gradient 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 staff has ascertained for the Estuaries Project region that while the per capita septic load is well constrained by direct studies, the consumptive use and nitrogen concentration data are less certain. As a result, the MEP has derived a combined term for an 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). Further, modeled and measured nitrogen loads were determined for a small sub-watershed to Mashapaquit Creek in West Falmouth Harbor (Smith and Howes, manuscript in review) where measured nitrogen discharge from the aquifer was within 5% of the modeled N load. Another evaluation was conducted by surveying nitrogen discharge to the Mashpee River in reaches with swept sand channels and in winter when nitrogen attenuation is minimal. The modeled and observed loads showed a difference of less than 8%, easily attributable to the low rate of attenuation expected at that time of year in this type of ecological situation (Samimy and Howes, unpublished data).

While census-based population data has limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water used based on average residential occupancy to measured average water uses. This is performed as a quality assurance check to increase confidence 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) and the reasonableness of the freshwater attenuation (Section IV.2) add additional weight to the nitrogen loading coefficients used in the MEP analyses and a variety of other MEP embayments. While the MEP septic system nitrogen load is the best estimate possible, to the extent that it may underestimate the nitrogen load from this source reaching receiving waters provides a safety factor relative to other higher loads that are generally used in regulatory situations. The lower concentration results in slightly higher amounts of nitrogen mitigation (estimated at 1% to 5%) needed to lower embayment nitrogen levels to a nitrogen target (*e.g.* nitrogen threshold, cf. Section VIII). The additional nitrogen removal is not proportional to the septic system nitrogen level, but is related to 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 Nauset Marsh watersheds, MEP staff reviewed US Census population values for the Towns of Orleans and Eastham. Since Brewster occupies a relatively small portion of the watershed, its information was not included in this validation analysis. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. Based on data collected during the 2000 US Census, average occupancy within Orleans was 2.05 people per housing unit with 61% of year-round occupancy of available housing units; 2010 Census results has a slight drop in these measures: 2.00 and 55%, respectively. Eastham population numbers are similar with similar drops in 2010: 2000 Census is 2.28 people per household with 43% year-round dwellings, while 2010 Census is 2.08 people per household with 40% year-round dwellings.

Comparison of average measured water use and water use estimates based on Census information show good agreement. Average water use for single-family residences with municipal water accounts in the Nauset Estuary MEP study area is 148 gpd. If this flow is multiplied by 0.9 to account for consumptive use, the study area wastewater flow average is 134 gpd. If the state Title 5 estimate of 55 gpd per capita is multiplied by average 2000 Census occupancy for Eastham and Orleans, the average water use per residence would be estimated at 125 gpd and 113 gpd, respectively. The corresponding flow estimates based on the 2010 Census occupancies are 114 gpd and 110 gpd, respectively. These Census-based flows do not include any adjustment for seasonal increases in occupancy. If it is assumed that average occupancy doubles for three months, the average town-wide water use for Orleans would rise to 156 gpd based on the 2000 Census data or 143 gpd based on the 2010 Census data. Corresponding Eastham estimates are 141 gpd and 137 gpd. With these reasonable seasonal adjustments, measured water use is approximately the same as the study area average water use. This analysis suggests that the average water use is reasonably reflective of average wastewater estimates.

At the outset of the MEP, project staff decided to utilize the water use approach for determining residential wastewater generation by septic systems because of the inherent difficulty in accurately gauging actual occupancy in areas impacted by seasonal population fluctuations, such as most of Cape Cod. Estimates of summer populations on Cape Cod derived from a number of approaches (*e.g.*, traffic counts, garbage generation, sewer use) suggest average population increases from two to three times year-round residential populations measured by the US Census. This analysis and the high proportion of seasonal homes in the Nauset Estuary watershed suggests that water use, on average, is a reasonable estimate of wastewater generation within the study area.

Water use information exists for 48% of the 2,705 developed parcels in the Nauset Marsh watershed. Given the lack of public water availability in Eastham, most of the parcels without water use are located in Eastham. Parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that are classified with land use codes that should be developed (*e.g.*, 101 or 325), have been confirmed as having buildings on them through a review of aerial photographs or town assessor valuations, and do not have a listed account in the water use databases. Of the 1,396 parcels without water use accounts, 1,242 (89%) are classified as single-family residences (land use code 101). These parcels are assumed to utilize private wells and were assigned the Nauset Estuary study area average water use of 148 gpd in the watershed nitrogen loading modules. Given the preponderance of residential land uses among developed parcels without water use accounts, all developed parcels without water use are also conservatively assigned 148 gpd as their water use in the watershed nitrogen loading model.

Alternative Site-specific Wastewater Estimates

During MEP assessments, MEP staff typically seek information on large wastewater treatment facilities and alternative denitrifying septic systems for site-specific modifications. Given Eastham's reliance on private wells for drinking water, in the Nauset Estuary MEP assessment, project staff also obtained regulatory water use information for public water supplies in Eastham from MassDEP (personal communication, Brian Dudley, 9/07). MassDEP staff also reviewed Groundwater Discharge Permits and found that no GWDPs exist within the Nauset Estuary watershed. GWDPs are required under MassDEP regulations for wastewater treatment systems with design flows greater than 10,000 gallons per day.

Review of MassDEP records found that there are 16 public water supplies in Eastham. These public water systems are individual on-site wells that serve the public and include municipal facilities, restaurants and condominiums. Reported annual water use from varying time frames between 2000 and 2006 was available for the properties. These annual rates were converted to averages. These averages were assigned to the respective sites.

The Barnstable County Department of Health and the Environment maintains a database of selected alternative, denitrifying septic systems and their performance removing nitrogen. Review of the nitrogen effluent discharge from nearly 500 of these systems used on single-family residences throughout the county is only marginally different than the factor used by the MEP (Heufelder, *et al*., 2007). Review of monitoring data from denitrifying septic systems in the Nauset Estuary watershed generally confirmed this finding. For example, for the nine (9) systems in the Eastham portion of the watershed (data provided by Brian Baumgaertel, BCDHE, 2/09), average total nitrogen concentration from these systems was 17.2 mg/l with a standard deviation of 14.6 (or 85% of the average). All of the Eastham systems are single-family residences. Given the large variability in total nitrogen concentrations from denitrifying septic systems, MEP staff maintained the standard MEP wastewater nitrogen loading factor for all developed properties in the Nauset Estuary watershed except for the Salt Pond Visitor Center. Support for this decision is also provided by the Town of Orleans CWMP, which stated that alternative septic systems treat less than 2% of the wastewater flow throughout the town (W-P, 2010).

The Salt Pond Visitor Center had monthly water use flows from March 2005 to March 2006 with three rounds of influent and effluent monitoring for various nitrogen species (J.Campopiano, 2006). This information was developed into a site specific, wastewater nitrogen load for the Visitor Center and this was incorporated into the watershed nitrogen loading model for Nauset Marsh.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized areas: lawns, golf courses, and cranberry bogs. Residential lawns are usually the predominant source within this category. In order to add this source to the watershed nitrogen loading model for the Nauset Estuarine System, MEP staff reviewed available regional information about residential lawn fertilizing practices. There are no golf courses or cranberry bogs in the Nauset Marsh watershed, so residential lawns is the predominant source of fertilizer nitrogen.

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 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 should also be noted that a recent technical review of lawn fertilizer leaching in settings similar to those on Cape Cod confirmed that the 20% leaching rate is appropriate (HWG, 2009). It is likely that these load rates still represent a conservative estimate of nitrogen load from residential lawns. It should also be noted that professionally maintained lawns in the three town survey were found to have the higher rate of fertilizer application than homeowner maintained lawns and hence a higher estimated annual nitrogen contribution to groundwater of 3 lb/lawn/yr.

Nitrogen Loading Input Factors: Eastham and Orleans Landfills

MEP staff contacted town staff to obtain any nitrogen monitoring data for the two solid waste sites within the Nauset Marsh system watershed: 1) the Town of Orleans landfill and 2) the Town of Eastham landfill. Development of nitrogen loads for each of these sites is based on the available monitoring data that is discussed below.

Orleans Landfill - The Orleans Landfill is located within the sub-watershed to Town Cove(sub-watershed #5). Groundwater contamination at the landfill site is monitored through a network of groundwater wells. Data from these wells was obtained through a review of Town of Orleans Board of Health files (personal communication, Bob Canning, 5/07). The landfill, which included septage lagoons, was closed and capped in 2005 (MassDEP SW database).

MEP staff reviewed twelve (12) sampling runs of groundwater monitoring data for the landfill from 1994 to 2007 (Town of Orleans BOH files). Groundwater samples were analyzed for nitrate-nitrogen (NO_3-N) only, so the organic and reduced portions of the nitrogen pool, if they occur, were missed. There is likely some unaccounted nitrogen since septage lagoons tend to be highly enriched in carbon and near field groundwater plumes can have reducing (anoxic) conditions. Wells down gradient of the primary area of solid waste had relatively low NO_3-N concentrations (for example, 1.3 mg/l at well 3S), consistent with reducing conditions in the near field. However, down-gradient wells from the former septage lagoons had much higher NO_3-N concentrations (for example, 11.4 mg/l at well 5S) indicative of oxidized conditions, with additional evidence that the near field plume region is also becoming more oxidized (*i.e.*, NO_3-N concentrations increased between 2005 and 2007). Based on the review of available groundwater monitoring data and other information in town Board of Health files, MEP staff determined the area of solid waste and the septage lagoons. Staff then reviewed the trends in NO_3-N concentrations over the available monitoring record in order to estimate the non-nitrate portion of the nitrogen load from the landfill. This effort resulted in a total nitrogen estimate from the former lagoons of 24.9 mg/l and 1.8 mg/l from the solid waste portion of the site. Using the recharge rate for the amount of water passing through the landfill combined with these concentrations results in an annual load of 50 kg from the area of the former lagoons and 68 kg from the solid waste area yielding a rounded total of 119 kg/yr from the Orleans landfill. The total annual load of 119 kg is added to the sub-watershed #5 load under existing conditions. At buildout, this load is removed due to the landfill cap and eventual flushing out of the groundwater aquifer.

It is acknowledged that this approach for estimating a nitrogen load from the Orleans landfill includes a number of assumptions, but these are appropriate based on the available data. A detailed assessment of all the available data is beyond the scope of the MEP, but staff balanced reasonable estimates of the various factors based on the general MEP guidance from MassDEP to include conservatism in nitrogen loading estimates when uncertainty exists in the data. A more refined evaluation and assessment of the established monitoring well network, including, at a minimum, sampling for and analysis of total nitrogen concentrations, would help to refine this assessment and future management options.

Eastham Landfill - The Eastham Landfill is located within the Minister Pond sub-watershed (sub-watershed #9). Groundwater contamination at the landfill site is monitored through a series of groundwater wells. Data from these wells was obtained through a review of the landfill's Comprehensive Site Assessment and through the landfill monitoring program of the Barnstable County Department of Health and the Environment. The landfill, which included septage lagoons, was closed and capped in 1997 (MassDEP Solid Waste database).

MEP staff reviewed nine (9) sampling runs of groundwater monitoring data for the landfill from 1994 to 1999. Groundwater samples were analyzed for nitrate-nitrogen (NO_3-N) during all runs and ammonium-nitrogen (NH_4^+-N) during the first six runs. There is likely some unaccounted nitrogen since septage lagoons also tend to release organic nitrogen forms. Wells down gradient of the former septage lagoons had extremely high NH_4^+-N concentrations, indicative of anoxia/reducing conditions within the near field (near the source) of the groundwater plume; for example, well MW-3i had a concentration of 349 mg/l on the July 22, 1996 sampling round. Wells down gradient of the primary area of solid waste had much lower nitrogen concentrations with more NO_3-N than NH_4^+-N. MEP staff determined the area of solid waste (8.8 acres) and the septage lagoons (0.4 acres) based on available maps. Staff then selected representative wells and nitrogen concentrations based on the most probable primary flow paths from the solid waste area and the former septage lagoons. Flow paths were determined through a review of head measurements and contaminant analysis. These selections resulted in the following total nitrogen concentrations: 187 mg/l at MW-3i (this well's average NH_4^+-N concentration) and 4.3 mg/l at MW-3s (this well's average NO_3-N concentration). Using the recharge rate as the amount of water passing through the site combined with these concentrations results in an annual load of 216 kg from the lagoons and 154 kg from the solid waste area and a rounded total nitrogen load of 369 kg/yr from the Eastham landfill. The total annual load of 369 kg is added to the sub-watershed #9 load under existing conditions. At buildout, this load is removed due to the landfill cap and eventual flushing out of the groundwater aquifer.

It is acknowledged that this approach for estimating a nitrogen load from the Eastham landfill includes a number of assumptions, but these are appropriate based on the available data. A detailed assessment of all the available data is beyond the scope of the MEP, but staff balanced reasonable estimates of the various factors based on the general MEP guidance from MassDEP to include conservatism in nitrogen loading estimates when uncertainty exists in the data. A more refined evaluation and assessment of the established monitoring well network, including, at a minimum, sampling and analysis of total nitrogen concentrations, would help to refine this assessment and future management options.

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas of the Nauset Estuary watershed assessment 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 Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and the MassDEP Nitrogen Loading Computer Model Guidance Document (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 Nauset Estuary watershed are summarized in Table IV-1.

Road areas are based on MassHighway GIS information, which provides road width for various road segments. MEP staff utilized the GIS to sum these segments and their various widths by sub-watershed. Project staff also checked this information against parcel-based rights-of-way.

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 sub-watershed and the sum of the area of the parcels within each sub-watershed. The resulting "parcelized" watersheds to the Nauset Estuary are shown in Figure IV-3.

Table IV-1. Primary Nitrogen Loading Factors used in the Nauset Marsh MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Harwich 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 (Orleans and Brewster) 24 (Eastham)
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:	
Natural Area Recharge	0.072	Existing developed parcels wo/water accounts and buildout residential parcels:	148 gpd[2]
Wastewater Coefficient	23.63		
Town of Eastham Landfill Load (kg/yr)	369		
Town of Orleans Landfill Load (kg/yr)	119	Eastham public water supply wells	MassDEP reported flows
Salt Pond Visitor Center Load (kg/yr)	122	Existing developed parcels w/water accounts:	Measured annual water use
Fertilizers:		Commercial and Industrial Buildings without/WU and buildout additions[3]	
Average Residential Lawn Size (sq ft)[1]	5,000	Commercial	
Residential Watershed Nitrogen Rate (lbs/lawn)[1]	1.08	Wastewater flow (gpd/1,000 ft2 of building):	98
Nitrogen loading rate	20%	Building coverage:	13%
Average Single Family Residence Building Size (based on other towns; sq ft)	1,500	Industrial	
		Wastewater flow (gpd/1,000 ft2 of building):	16
		Building coverage:	10%

Notes:
1) Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.
2) Based on average measured flow in all single-family residences in the watershed
3) Based on characteristics of Orleans land uses: existing water use for similarly classified properties

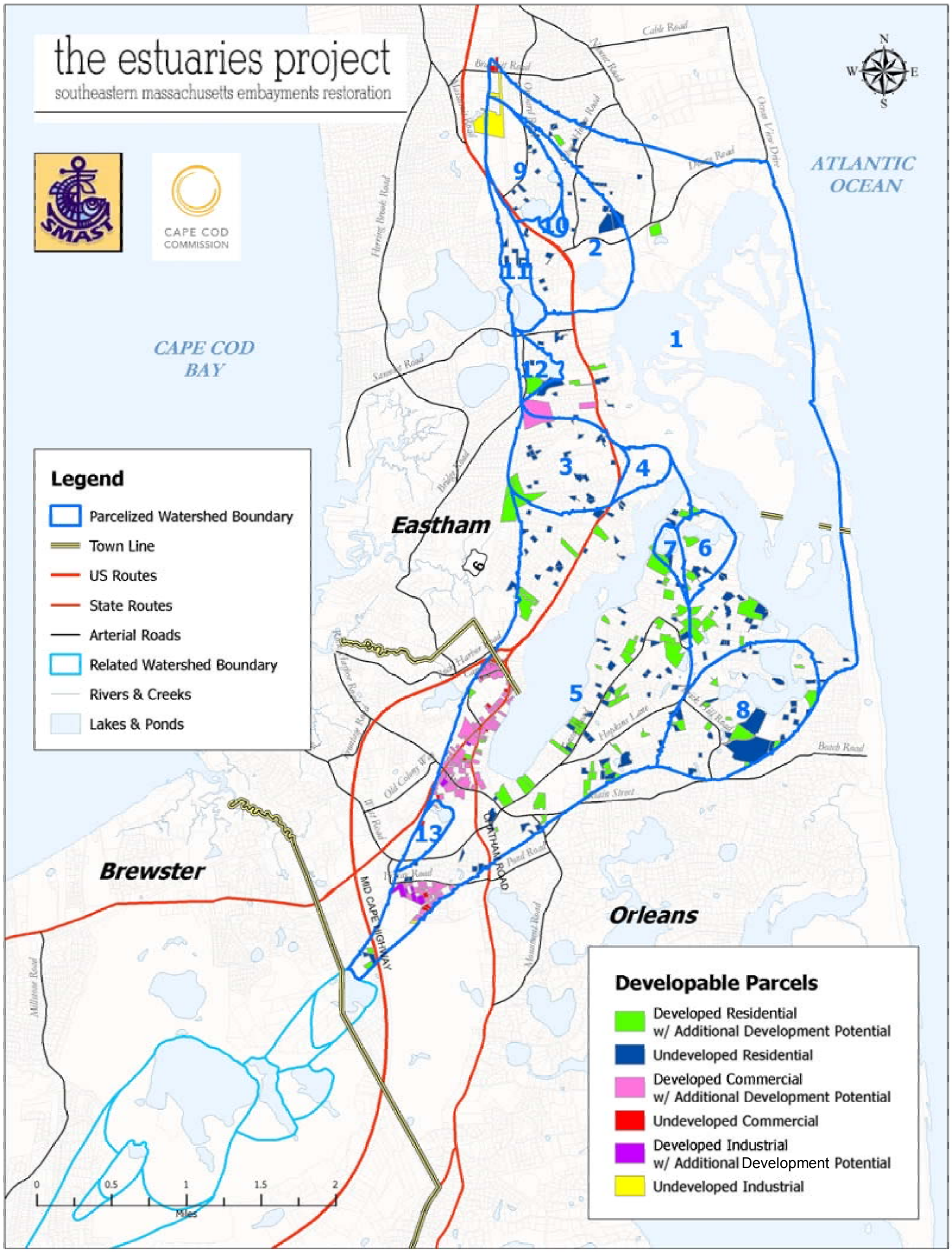


Figure IV-3. Parcels, Parcelized Watersheds, and Developable Parcels in the Nauset Estuary watersheds. Parcels colored green, pink, and purple are developed parcels (residential, commercial, and industrial, respectively) with additional development potential based on current town zoning, while parcels colored blue, red, and yellow are corresponding undeveloped parcels, respectively, classified as developable by the respective town assessors. The parcelized watersheds are drawn to minimize the division of properties for management purposes while achieving a match of area with the modeled watersheds of 2% or less. The amount of additional development is predominantly based on minimum lot sizes specified in town zoning; these parcels are assigned estimated nitrogen loads in MEP buildout calculations. All buildout results were reviewed with respective town staff.

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 Nauset Estuary. The assignment effort was undertaken to better define sub-estuary loads and enhance the use of the Linked Watershed-Embayment Modeling Approach for the analysis of management alternatives.

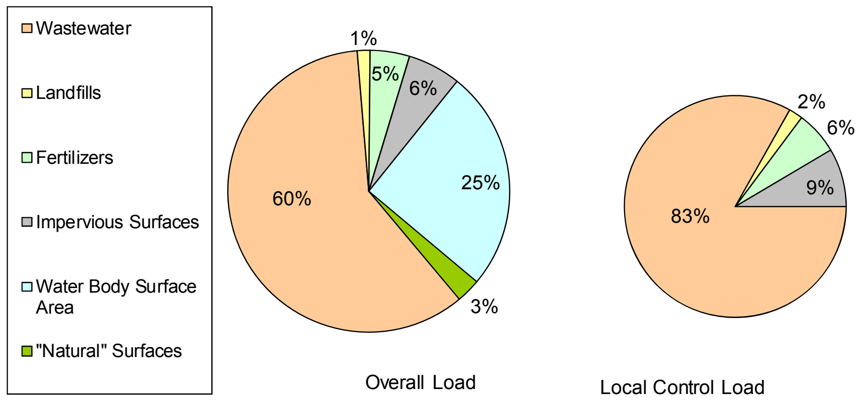
Following the assignment of all parcels, sub-watershed modules were generated for each of the 13 sub-watersheds in the Nauset Estuary study area. These sub-watershed modules summarize, among other things: water use, parcel area, parcel frequency by land use category, private wells, and road area. All relevant nitrogen loading data is assigned to each sub-watershed. Individual sub-watershed information is then integrated to create the Nauset Estuary Watershed Nitrogen Loading module with summaries for each of the individual 13 sub-watersheds plus the appropriate portion of the nitrogen load from Baker Pond. The sub-watersheds are generally paired with functional embayment/estuary basins for the Linked Watershed-Embayment Model's water quality component.

For management purposes, the aggregated estuary watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Nauset Estuary study area, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), town landfills, fertilizers, 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 basins comprising the Nauset Estuary, by each source category (Figure IV-4). 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 waters before use in the embayment water quality sub-model (Section IV.2).

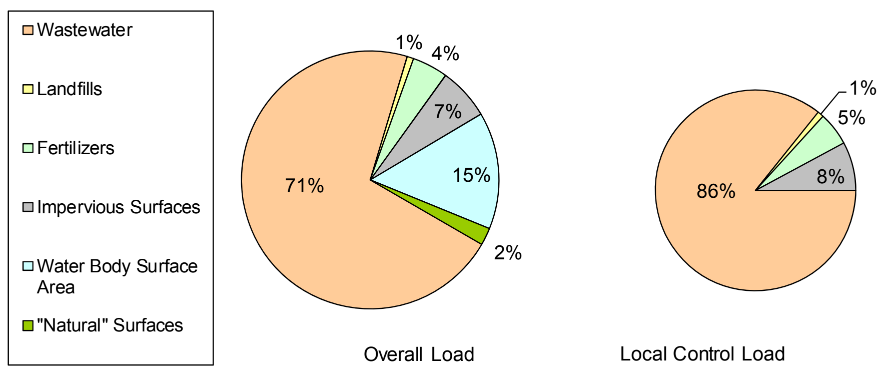
One of these attenuation adjustments is associated with passage through freshwater ponds. Since groundwater outflow from a pond can enter more than one down gradient sub-watershed, the length of shoreline on the down gradient side of the pond is used to apportion the pond-attenuated nitrogen load to respective down gradient sub-watersheds. The apportionment is based on the percentage of discharging shoreline bordering each down gradient sub-watershed. In the Nauset Estuary watershed, this occurs for ponds completely within the watershed (*e.g.*, Depot Pond) and the ponds located along the outer boundary of the watershed (*e.g.*, Baker Pond). At Baker Pond, for example, the pond has 2,436 feet of down gradient shoreline; 40% of that shoreline being up-gradient of the Town Cove sub-watershed and the other portion being split among three sub-watersheds that discharge to Pleasant Bay (Howes, *et al.*, 2006). This breakdown of the water discharge from Baker Pond means that 40% of the accompanying attenuated nitrogen load that leaves the pond reaches Town Cove and 60% travels toward Pleasant Bay. Similar pond-specific calculations were completed wherever pond flows and nitrogen loads were divided among a number of down gradient receiving sub-watersheds.

Table IV-2. Nauset Estuary Watershed Nitrogen Loads. Attenuated nitrogen loads are based on measured and assigned attenuation factors for streams and freshwater ponds. Stream attenuation factors are based on measured loads (see Section IV.2), while pond attenuation factors are assigned a standard MEP nitrogen attenuation of 50% unless measured attenuation rates are available based on MEP data review or water quality monitoring from the Cape Cod Pond and Lake Stewards program. All nitrogen loads are kg N yr^{-1}.

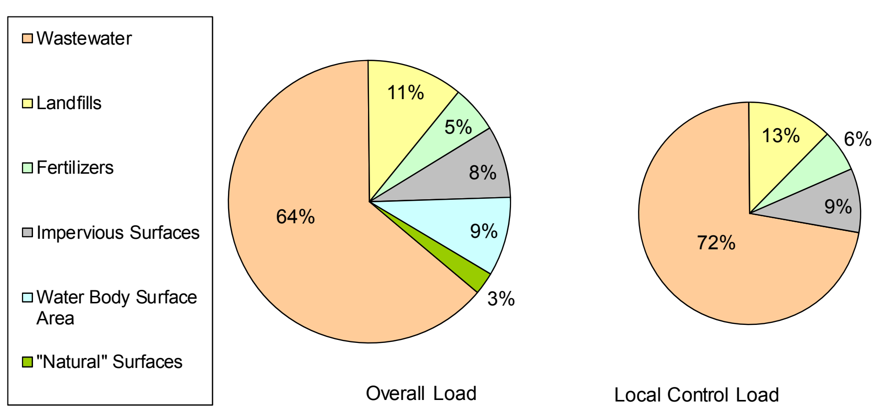
		Nauset Marsh N Loads by Input (kg/y):							% of Pond Outflow	Present N Loads			Buildout N Loads		
Name	Watershed ID#	Wastewater	Landfills	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Nauset Marsh System		16677	408	1262	1704	7064	775	2305		27891		26080	30196		28390
Nauset Marsh	1	2805	0	293	355	3	315	586		3770		3770	4356		4356
Mill Pond Salt	8	1468	0	135	140	0	57	354		1800		1800	2154		2154
Woods Cove	6	220	0	18	21	0	13	34		272		272	305		305
Muddy Pond	12	174	0	18	22	49	6	39		269	70%	81	308	70%	92
Depot Pond	11	136	0	16	15	88	7	35	70%	262	75%	66	298	75%	74
Nauset Marsh Estuary Surface						4107				4107		4107	4107		4107
Mill Pond Salt Estuary Surface						390				390		390	390		390
Woods Cove Estuary Surface						88				88		88	88		88
Town Cove Total		10198	119	641	934	2100	310	1297		14301		13566	18942		14780
Town Cove	5	8724	119	501	757	2	239	1087		10340		10340	11427		11427
Rachel Cove	7	51	0	5	6	0	3	6		65		65	70		70
Boland Pond	13	182	0	7	14	22	7	11		232	50%	116	243	50%	122
Mary Chase Rd Gauge	3	1065	0	110	131	0	38	146		1344	35%	874	1490	35%	968
Nauset Stream	4	111	0	11	19	0	8	6		150		150	156		156
Baker Pond	BP	66	0	7	7	108	15	41	40%	202	65%	53	243	65%	67
Town Cove Estuary Surface						1909				1909		1909	1909		1909
Rachel Cove Estuary Surface						59				59		59	59		59
Nauset Stream Estuary Surface						1				1		1	1		1
Salt Pond		1677	290	142	217	238	67	-40		2631		1940	2591		2043
Salt Pond	2	1130	0	99	161	0	44	191		1435		1435	1626		1626
Minister Pond	MP	412	247	30	41	52	16	-209	67%	799	65%	280	590	65%	206
Schoolhouse Pond Total	SP	76	43	6	7	39	4	-36		175	50%	88	139	50%	70
Depot Pond	11	58	0	7	7	38	3	15	30%	112	75%	28	127	75%	32
Salt Pond Estuary Surface						109				109		109	109		109
Ponds															
Depot Pond	11	194	0	23	22	126	10	51		374	75%	94	425	75%	106
Minister Pond	9	617	369	45	62	78	24	-313		1195	65%	418	882	65%	309
Schoolhouse Total	SP	76	43	6	7	39	4	-36		175	50%	88	139	50%	70
Schoolhouse Pond	10	5	0	0	0	30	1	0		37		37	37		37
Minister Pond	MP	71	43	5	7	9	3	-36	33%	139		139	102		102



a. Nauset Marsh Estuary System



b. Town Cove Estuary System



c. Salt Pond Estuary System

Figure IV-4. Land use-specific unattenuated nitrogen loads (by percent) to the a) whole Nauset Estuary watershed, b) the Town Cove sub-watershed, and c) the Salt Pond sub-watershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be managed under local regulatory control.

Freshwater Pond Nitrogen Loads

Freshwater ponds on Cape Cod are generally sites of natural nitrogen reduction (or attenuation) prior to the nitrogen reaching an estuary. These ponds are generally kettle hole depressions that intercept the surrounding groundwater table revealing what some call "windows on the aquifer." Groundwater typically flows into the pond along the up-gradient shoreline, then lake water flows back into the groundwater system along the down gradient shoreline. Occasionally a Cape Cod pond will also have a stream outlet, which is often a herring run, that also acts as a discharge point. Since the nitrogen loads flow into the pond with the groundwater, the relatively more productive pond ecosystems incorporate some of the nitrogen, retain some nitrogen in the sediments, and change the nitrogen among its various oxidized and reduced forms. As result of these interactions, some of the nitrogen is removed from the estuary watershed system, mostly through burial in the pond sediments and denitrification that returns it as N_2 to the atmosphere. Following these transformations, the remaining (attenuated) loads flow back into the groundwater system along the down gradient side of the pond and eventual discharge into the down gradient embayment or through a stream outlet directly to the estuary. The nitrogen load summary in Table IV-2 includes both the unattenuated (nitrogen load to each sub-watershed) and attenuated nitrogen loads.

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

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

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

Many ponds on Cape Cod have been sampled through the regional Cape Cod Pond and Lake Stewards (PALS) Snapshots and the initiative of local volunteer pond sampling programs.

The PALS Snapshots are regional volunteer pond once per year samplings supported for the last ten years by SMAST and the Cape Cod Commission, with free laboratory services provided by the Coastal Systems Program Laboratory at SMAST. Sampling protocols developed through the PALS program (Eichner *et al*., 2003) have been used for more extensive pond sampling programs in many communities on Cape Cod, including Eastham (Eichner, 2009) and Orleans (Eichner, 2007). Sampling under these protocols has included field collection of temperature and dissolved oxygen profiles and sampling of standardized depths that include some evaluation of the impact of sediment nutrient regeneration. PALS water samples are analyzed at the SMAST laboratory for total nitrogen, total phosphorus, chlorophyll *a*, alkalinity, and pH. In some cases town programs have generated sufficient sampling data that modified MEP nitrogen attenuation rates can be reliably assigned to freshwater ponds.

Within the Nauset Estuary watershed, there are six (6) freshwater ponds with delineated watersheds: Baker, Boland, Minister, Schoolhouse, Depot and Muddy/Mill. All of these ponds have available pond-wide bathymetric data and water quality data.

In order to further evaluate whether a site-specific nitrogen attenuation rate could be assigned to the ponds, MEP staff reviewed the available water quality monitoring data. Eastham pond data for Minister, Schoolhouse, Depot and Muddy/Mill ponds have been summarized in Eichner (2009), while Orleans pond data for Baker and Boland are summarized in Eichner (2007). These data includes sampling results collected by town volunteers generally following PALS sampling protocols and sample analyses at the SMAST-CSP Analytical Facility and the Cape Cod National Seashore lab.

MEP staff reviewed the available pond data to assess its variability and potential issues for determining nitrogen attenuation. Review of available data found that most data was focused on late spring, summer, and early fall months, with very limited data between October and March. Additional pond data is necessary to resolve annual attenuation rate uncertainty and for this reason, MEP staff tended to use more conservative attenuation rates than those based strictly on the available data.

Eichner (2009) indicated that Schoolhouse and Minister have “extensive internal sediment demand”, essentially share the same watershed, and share a surface connection that is thought to make Minister Pond function as a cleansing basin and recipient of most of the watershed load. The review also found that concentrations from some of the sampling runs appeared to be “flipped” with higher surface concentrations and lower, near-sediment concentrations. Review of the nitrogen data (with data assigned to what are thought to be appropriate depths) indicates that attenuation in Minister Pond should be 77% and 90% in Schoolhouse Pond. In order to address the uncertainties in the data and the system characterization (e.g., role of sediment regeneration in the measured nitrogen concentrations, updated bathymetry, and the role of nitrogen export from one pond to the other via the hydrologic connection), MEP staff included modified, more conservative attenuation rates in the Nauset Marsh nitrogen loading model for Minister and Schoolhouse ponds. Minister data was more stable with less uncertainties and a 65% attenuation rate was assigned, while Schoolhouse data has more uncertainties, especially over the hydro-connection impact, and for this reason was assigned the MEP standard 50% attenuation rate (Table IV-3).

Boland presents somewhat of a similar picture with significant sediment oxygen demand, temperature stratification that is unusual for such a shallow pond, and an uncertain role of nutrient regeneration (Eichner, 2007). Review of the nitrogen data indicates that Boland has a calculated 64% attenuation, but in order to address the uncertainties in the data and the system characterization (*e.g.*, role of sediment regeneration and temperature stratification), MEP staff chose to use the standard MEP attenuation rate of 50% for Boland Pond in the Nauset Estuary nitrogen loading model.

Table IV-3. Nitrogen attenuation by Freshwater Ponds in the Nauset Estuary watershed based upon town volunteer sampling and Cape Cod Pond and Lakes Stewardship (PALS) program sampling (Eichner, 2007 and Eichner, 2009). These data were collected to provide a site-specific check on nitrogen attenuation by these systems. Ponds in the watershed are assigned the standard MEP nitrogen attenuation value of 50% unless the MEP data review suggests that a higher attenuation rate can be supported. The listed attenuation rates are those that are assigned for these ponds in the Nauset Estuary MEP nitrogen loading model.

Pond	PALS ID	Area Acres	Maximum Depth m	Overall volume turnover time yrs	# of TN samples for N Attenuation calculation	Assigned N Load Attenuation %
Baker	OR-167	28.85	18.0	1.18	17	50% std
Boland	OR-136	4.70	4.6	0.35	17	50% std
Minister	EA-92	17.33	5	0.27	18	65%
Schoolhouse	EA-93	6.76	4.5	1.08	13	50% std
Depot	EA-96	26.7	12	2.58	32	75%
Muddy	EA-102	10.1	2	0.35	28	70%

Data sources: all areas from CCC GIS; all maximum depths are maximum recorded depths from citizen sampling; number of Total Nitrogen samples available for attenuation calculations are surface concentrations from town monitoring and annual PALS Snapshot provided by SMAST lab; available bathymetry from MassDFW bathymetric maps or data collected by volunteers (www.mass.gov/dfwele/dfw/dfw_pond.htm, Eichner, 2009).

Depot and Muddy ponds generally had less uncertainty in their respective nitrogen concentrations than Minister/Schoolhouse, although also lacking sediment regeneration and updated bathymetric data. Based on the available water quality data, these ponds have calculated nitrogen attenuation rates of 82% and 73%, respectively. In order to address some of the data uncertainties (e.g., lack of sediment samples to evaluate the impact of sediment regeneration on surface TN concentrations), MEP staff rounded the rates down to slightly more conservative percentages: 75% and 70%, respectively. Baker Pond was assigned a standard 50% nitrogen attenuation rate in the Pleasant Bay MEP Report (Howes, et al., 2006) and this rate is not changed in the Nauset Estuary nitrogen loading model.

Buildout

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

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

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

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

Following the completion of the initial buildout assessment for the Nauset Estuary watersheds, MEP staff reviewed the results with town officials. The initial analysis for Nauset Estuary was completed in 2007 and project staff discussed development changes that occurred in the interim with Orleans and Eastham staff. MEP staff reviewed the preliminary buildout with Eastham staff on February 15, 2011 and with Orleans Planning staff on February 16, 2011.

Eastham staff forwarded results from a buildout assessment completed by Stearns and Wheler (2009); these results were incorporated in the MEP buildout. Town of Orleans Planning staff reviewed changes that had occurred since 2007 and forwarded a list of changes (personal communication, George Meservey, Director of Planning & Community Development).

The predominant changes occurred in the development of developable residential properties, *e.g.*, conversion of developable residential properties (land use codes of 130 and 131) to single family residences (land use codes 101). Given that the primary water quality data collected for the MEP assessment is closer to 2007, MEP staff included the changes that have occurred since 2007 into the Nauset Marsh watershed buildout scenario.

All the parcels with additional buildout potential within the Nauset Estuary watershed are shown in Figure IV-3. Each additional residential, commercial, or industrial property added at buildout is assigned nitrogen loads for wastewater and impervious surfaces. Residential additions also include lawn fertilizer nitrogen additions. All wastewater loads are assumed to come from on-site septic systems. Cumulative unattenuated buildout loads are indicated in a separate column in Table IV-2. Buildout additions within the Nauset Estuary watersheds will increase the unattenuated nitrogen loading rate by 8%.

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-watersheds of the Nauset Estuarine System 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 regions of the Nauset Estuary 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, a portion of the nitrogen load passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. 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 (i.e. removal, not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed. In the watershed for the Nauset Estuary, only a small portion of the freshwater flow and transported nitrogen passes through a stream (e.g. Creek discharging from Mary Chase Marsh adjacent to Town Cove, Figure IV-5) prior to entering the Nauset Harbor estuary, providing the opportunity for significant nitrogen attenuation. However, multiple kettle ponds within the watershed also support nitrogen removal (see Table IV-3).

Figure IV-5. Location of Stream gauge (red symbol) on the small creek, Mary Chase Creek, discharging to outer Town Cove within the Nauset Estuarine System.

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, 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). Attenuation by freshwater ponds (see Section IV.1.3, above) and in surface water flows vary in their relative importance based upon the specific watershed. An example of the combined effect of surface freshwater systems in attenuation relating to embayment nitrogen management was seen in the Agawam River (Wareham, MA), 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 (Falmouth, MA) 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, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP Approach. MEP conducted long-term measurements of natural attenuation relating to surface water discharge to the perimeter of the Nauset Estuary System (specifically Town Cove) in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). These additional site-specific studies were conducted in the single major surface water flow system discharging to the outer reach of Town Cove portion, Mary Chase Marsh Creek.

Quantification of watershed based nitrogen attenuation is contingent upon being able to compare nitrogen load to the embayment system directly measured in freshwater stream flow (or in tidal marshes, net tidal outflow) to nitrogen load as derived from the detailed land use analysis (Section IV.1). Measurement of the flow and nutrient load associated with the freshwater stream discharging to the estuary provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area upgradient from the various gauging sites. Flow and nitrogen load were determined at the gauge location for 24 months of record (Figure IV-6). During the study period, a velocity cross-section was completed on the creek every month to two months. Volumetric flow was determined from the stream cross-sectional area associated with each velocity measurement. The total flow (instantaneous stream flow), Q, being the sum of the individual cross-sectional component flows (i.e. multiple measurements) made across the stream, each point describing a specific portion of the stream cross-section.

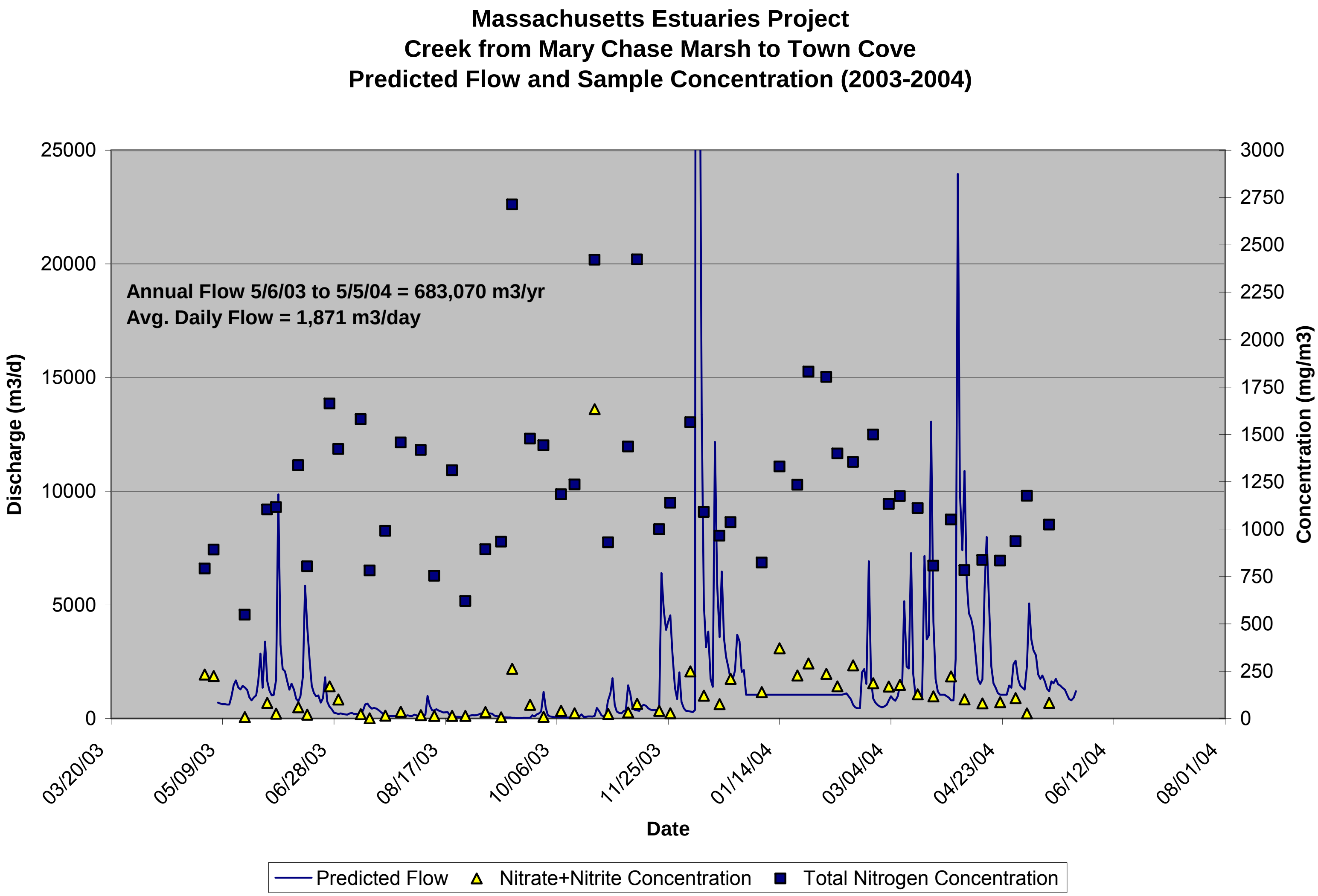


Figure IV-6. Creek discharge from Mary Chase Marsh / Fort Hill (solid blue line), nitrate+nitrite (yellow triangle) and total nitrogen (blue square) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Town Cove (Table IV-4).

Determination of stream flow at the gauge on Mary Chase Marsh Creek 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.

Periodic measurement of flows over the entire stream gauge deployment period allowed for the development of a stage-discharge relationship (rating curve) that could be used to obtain flow volumes from the detailed record of stage measured by the continuously recording stream gauges. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given river. These hourly stages values were then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. A complete annual record of stream flow (365 days) was generated for the surface water discharge flowing into the Town Cove / Nauset Estuary from the Creek flowing out of Mary Chase Marsh in the vicinity of Fort Hill.

The annual flow record for the surface water flow at the gauge was merged with the nutrient data set generated through the weekly water quality sampling performed at the gauge location to determine nitrogen loading rates to the outer reach of the Town Cove portion of Nauset Estuary. Nitrogen discharge from the stream was calculated using the paired daily discharge and daily nitrogen concentration data to determine the mass flux of nitrogen through the specific gauging site. For the stream gauge location, weekly water samples were collected (at low tide for a tidally influenced stage) in order to determine nutrient concentrations from which nutrient load was calculated. In order to pair daily flows with daily nutrient concentrations, interpolation between weekly nutrient data points was necessary. These data are expressed as nitrogen mass per unit time (kg/d) and can be summed in order to obtain weekly, monthly, or annual nutrient load to the embayment system as appropriate. Comparing these measured nitrogen loads based on stream flow and water quality sampling to predicted loads based on the land use analysis allowed for the determination of the degree to which natural biological processes within the watershed to the gauged stream currently reduces (percent attenuation) nitrogen loading to the overall embayment system.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Creek Discharge from Mary Chase Marsh / Fort Hill

Mary Chase Marsh, located upgradient of the gauge site (between Route 6 and Governor Prence Road) is a small freshwater/brackish marsh and like similar marshes on Cape Cod, this marsh has stream outflow that is measurable and can be sampled for nutrient related water quality. While this stream outflow may serve to decrease the attenuation of nitrogen by this marsh system due to decreased residence time, it also provides for a direct measurement of the amount of nitrogen attenuation. In addition, nitrogen attenuation also occurs within riparian zones for streams and streambed associated with the creek out of Mary Chase Marsh. The combined rate of nitrogen attenuation by these processes was determined by comparing the existing nitrogen loading to the sub-watershed region contributing to Mary Chase Marsh Creek above the gauge site (Figure IV-5) based on the land-use module and the measured annual discharge of nitrogen from the stream study, Figure IV-6.

At the Mary Chase Marsh Creek gauge site, a continuously recording vented calibrated water level gauge was installed to yield the level of water in the freshwater portion of the Creek that carries the flows and associated nitrogen load to Town Cove. As the lowermost portion of Mary Chase Marsh Creek is tidally influenced, the gauge was located upstream, such that freshwater flow could be measured at low tide. Due to site constraints, flow at the gauge site was still slightly tidally influenced at low tide and as such the flow record had to be adjusted to compensate for the tidal influence. To confirm the degree to which freshwater was being measured the stage record was analyzed for any semi-diurnal variations indicative of tidal influence and salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average low tide salinity was determined over several discrete periods when salinity in the creek shared similar characteristics. For the period May 1, 2003 to June 26, 2003 average salinity was 5.1 ppt. For the period June 30, 2003 to October 29, 2003 the average salinity was 14.3 ppt. and for the period November 7, 2003 to May 28, 2004 average salinity was 3.3 ppt. Therefore, the gauge location while sub-optimal was deemed acceptable for making freshwater flow measurements understanding that predicted flows at this location would have to be salinity adjusted. Calibration of the gauge was checked monthly. The gauge on Mary Chase Marsh Creek was installed on September 6, 2002 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued until August 1, 2004 for a total deployment of 24 months. The deployment period was extended due to vandalism of the gauge as well as instrument failures. Ultimately, a valid one year record was obtained, May 6, 2003 to May 5, 2004.

Stream flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Mary Chase Marsh Creek site based upon these flow measurements and measured water levels at the gauge site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the mouth of the Town Cove sub-embayment and was reflective of the biological processes occurring in the creek channel and bordering marsh zone contributing to nitrogen attenuation (Figure IV-6, Table IV-4 and Table IV-5). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at the gauge site.

Table IV-4. Comparison of water flow and nitrogen discharges from Creek (freshwater) discharging from Mary Chase Marsh to Town Cove portion of Nauset Harbor estuarine system. The "Stream" data is from the MEP stream gauging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	Mary Chase Marsh Creek Discharge[a] Town Cove / Nauset	Data Source
Total Days of Record	365[b]	(1)
Flow Characteristics		
Stream Average Discharge (m3/day) **	1,871	(1)
Contributing Area Average Discharge (m3/day)	1,791	(2)
Discharge Stream 2004-05 vs. Long-term Discharge	4%	
Nitrogen Characteristics		
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.150	(1)
Stream Average Total N Concentration (mg N/L)	1.306	(1)
Nitrate + Nitrite as Percent of Total N (%)	11%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	2.44	(1)
TN Average Contributing UN-attenuated Load (kg/day)	3.68	(3)
Attenuation of Nitrogen in Pond/Stream (%)	34%	(4)

(a) Flow and N load to stream discharging from Mary Chase Marsh to Town Cove / Nauset Estuary includes apportionments of Pond contributing areas as applicable.
(b) May 6, 2003 to May 5, 2004 deployment period due to instrument malfunctions.
** Flow is an average of annual flow for 2003-2004

(1) MEP gage site data
(2) Calculated from MEP watershed delineations to ponds upgradient of specific gages; the fractional flow path from each sub-watershed which contribute to the flow in the creek to Town Cove.; and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates.
(4) Calculated based upon the measured TN discharge from the creek vs. the unattenuated watershed load.

Table IV-5. Summary of annual volumetric discharge and nitrogen load from Creek discharge from Mary Chase Marsh to Town Cove in the vicinity of Fort Hill based upon the data presented in Figures IV-6 and Table IV-4.

Embayment System	Period of Record	Discharge (m^3/year)	Attenuated Load (Kg/year)	
			NOx	TN
Town Cove Mary Chase Marsh Creek (MEP)	May 6, 2003 to May 5, 2004	683,070	100	892
Town Cove Mary Chase Marsh Creek (CCC)	Based on Watershed Area and Recharge	653,715	-	-

The annual freshwater flow record for Mary Chase Marsh Creek measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from Mary Chase Marsh Creek was only 4% above the long-term average modeled flows. The average daily flow based on the MEP measured flow data for one hydrologic year beginning May 6, 2003 and ending May 5, 2004 was 1,871 m^3/day compared to the long term average flows determined by the USGS modeling effort (1,791 m^3/day). The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Mary Chase Marsh Creek was considered to be negligible and the associated nitrogen load was quite small. The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the Creek discharging from Mary Chase Marsh would indicate that the Creek is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Mary Chase Marsh Creek outflow were elevated over background but only moderately compared to other streams on Cape Cod, 1.306 mg N L^{-1}. The stream flow and concentration data were integrated yielding an average daily total nitrogen discharge to the estuary of 2.44 kg/day and a measured total annual TN load of 892 kg/yr. In Mary Chase Marsh Creek (freshwater), nitrate was significantly less than half of the total form of nitrogen (11%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the marsh system was largely transformed to organic forms by plants and other biological activity occurring in that discrete ecosystem. This is consistent with the observation that dissolved and particulate organic nitrogen constitute 68 percent of the total nitrogen load in the stream discharge from Mary Chase Marsh. The low concentration of inorganic nitrogen in the out flowing waters of the creek also suggests that plant production and biologic activity within the up gradient freshwater portions of the ecosystem is potentially nitrogen limited. In addition, the low nitrate level suggests the possibility for additional uptake by freshwater systems is unlikely in this system. Opportunities for enhancing nitrogen attenuation elsewhere in the overall watershed to the Nauset Estuarine System could be considered, however there is not likely to be much more natural attenuation to be gained from the Mary Chase Marsh sub-watershed.

From the measured nitrogen load discharged by Mary Chase Marsh Creek to Town Cove and the nitrogen load determined from the watershed land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport through the wetland and creek to the estuary. Based upon lower total nitrogen load (892 kg yr^{-1}) discharged from the “freshwater” Creek compared to that added by the various land-uses to the associated watershed (1,344 kg yr^{-1}), the integrated attenuation in passage through freshwater wetlands prior to discharge to the estuary is 35% (i.e. 35% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the hydrologic and biogeochemical characteristics of the up gradient wetland capable of attenuating nitrogen. The directly measured nitrogen loads from the Creek was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

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 throughout the Nauset Estuary System. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Water column 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 Nauset Estuary predominantly in highly bio-available forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bio-available form nitrate. This nitrate and other bio-available forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like Cape Cod Bay). 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 sediments. 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 associated nitrogen “load” become incorporated into the surficial sediments of the system.

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 bio-available nitrogen is returned to the embayment water column 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 salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, such as found within much of the bordering region to the nearby Lewis Bay main basin. In contrast, regions of high deposition like Hyannis Inner Harbor, which is essentially a dredged boat basin, typically support anoxic sediments with elevated rates of nitrogen release during summer months. The consequence of this deposition is that these basin sediments are unconsolidated, organic rich and sulfidic nature (MEP field observations).

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading to the Nauset Estuary System. 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-water column nitrogen exchange

For the Nauset Estuary, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), a total of 32 sediment samples at 31 sites were collected and incubated under *in situ* conditions. Sediment samples were collected from each of the component basins with a total of 11 sites in Town Cove , 2 sites in Nauset Bay, 2 sites in Salt Pond, 3 sites in Mill Pond, 2 sites in Wood Cove and the remainder of the core locations were distributed throughout the marsh filled lagoon of Nauset Marsh (Figure IV-7). All the sediment cores for this system were collected in July-August 2003. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The number of core samples from each site (Figure IV-7) per incubation are as follows:

Nauset Estuary and Town Cove Benthic Nutrient Regeneration Cores

- NI-1 1 core (Salt Pond Bay)
- NI-2 1 core (Salt Pond Bay)
- NI-3 1 core (Salt Pond Bay)
- NI-4 1 core (Nauset Harbor/Marsh)
- NI-5 1 core (Nauset Harbor/Marsh)
- NI-6 1 core (Nauset Harbor/Marsh)
- NI-7 1 core (Nauset Harbor/Marsh)
- NI-8 1 core (Nauset Harbor/Marsh)
- NI-9 1 core (Town Cove)
- NI-10 1 core (Town Cove)
- NI-11 1 core (Town Cove)
- NI-12 1 core (Town Cove)
- NI-13 1 core (Town Cove)
- NI-14 1 core (Town Cove)
- NI-15 1 core (Town Cove)
- NI-16 1 core (Town Cove)
- NI-17 1 core (Town Cove)
- NI-18 1 core (Town Cove)
- NI-19 1 core (Town Cove)
- NI-20 1 core (Nauset Harbor/Marsh)
- NI-21 1 core (Nauset Harbor/Marsh)
- NI-22 1 core (Wood Cove)
- NI-23 1 core (Wood Cove)
- NI-24 1 core (Nauset Harbor/Marsh)

- NI-25 1 core (Salt Pond)
- NI-26 1 core (Salt Pond)
- NI-27 1 core (Nauset Bay)
- NI-28 1 core (Nauset Bay)
- NI-29 1 core (Mill Pond)
- NI-30 1 core (Mill Pond)
- NI-31/32 2 cores (Mill Pond)

Sampling was distributed throughout the primary component basins of system as well as the tributary sub-embayments such as Salt Pond, Wood Cove and Mill Pond. The benthic regeneration results for each site were combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

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

Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA. The laboratory follows standard methods for saltwater analysis and sediment geochemistry.

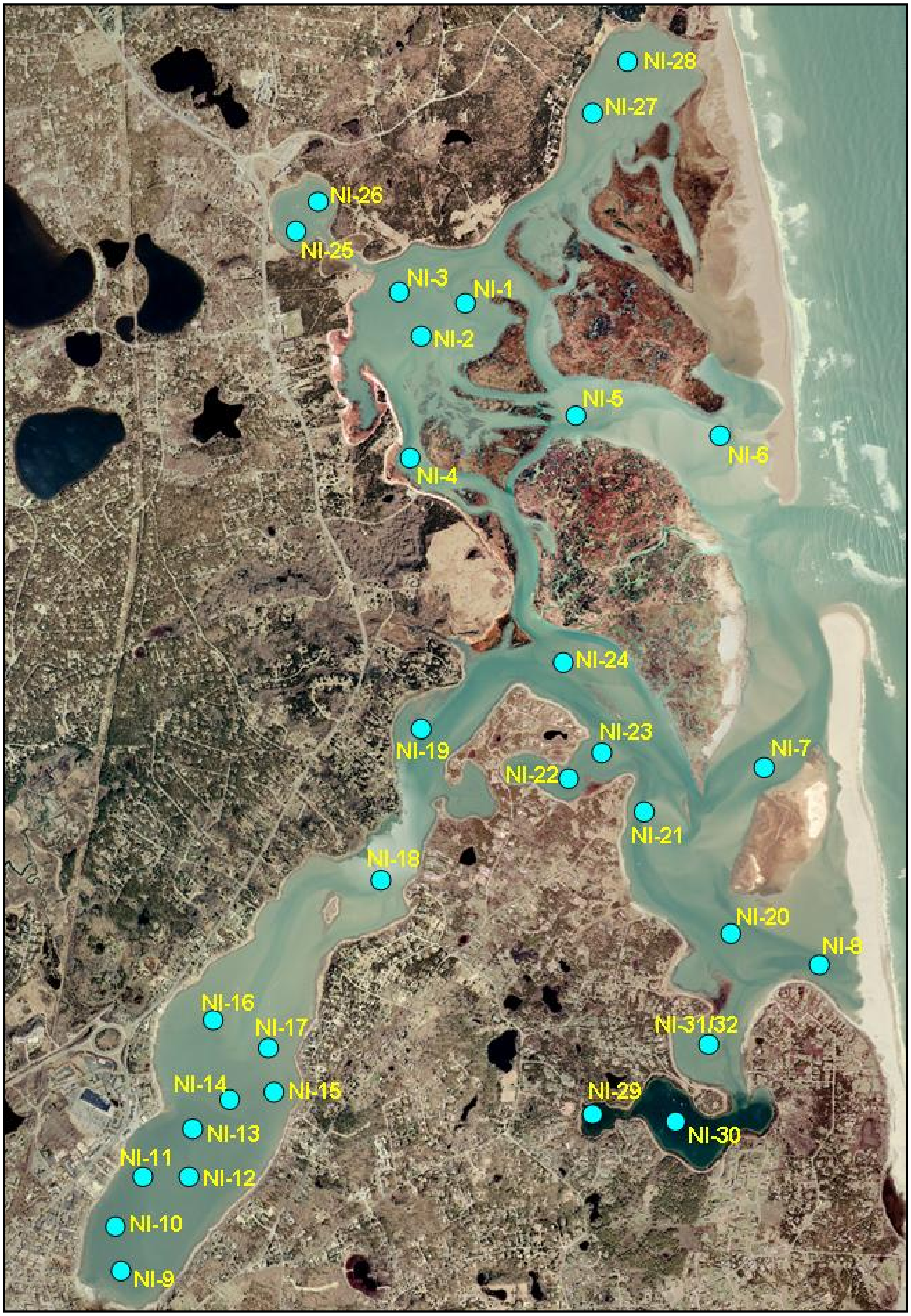


Figure IV-7. Nauset Estuary sediment sampling sites (blue dots) for determination of nitrogen regeneration rates. Numbers refer to station identifications listed above.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

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

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

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

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

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can “escape” to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-8).

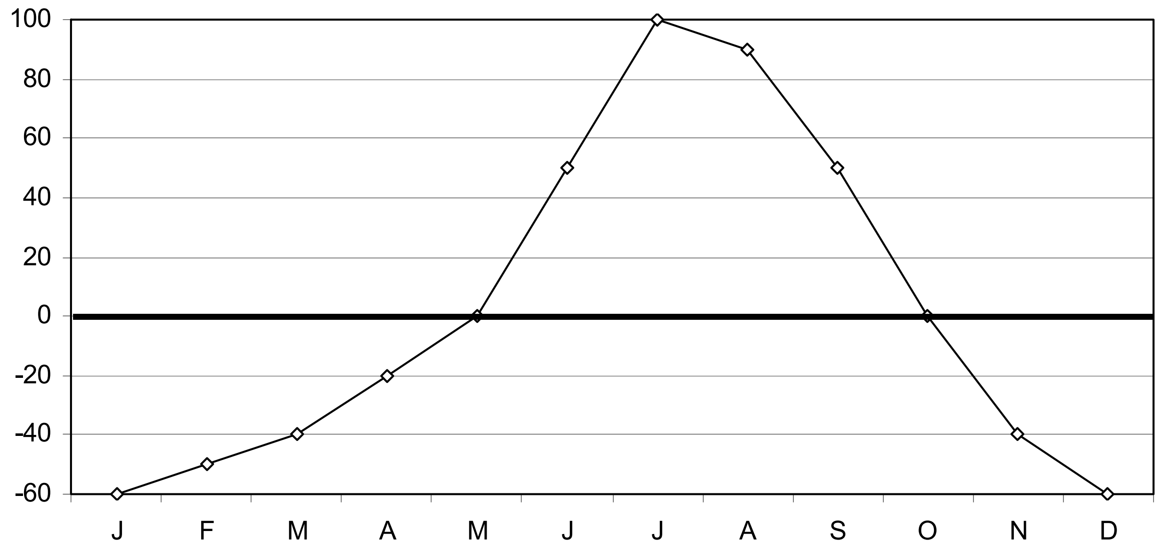


Figure IV-8. Conceptual diagram showing the seasonal variation in sediment N flux (mg N m^{-2} d^{-1}), with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

In order to determine the net nitrogen flux between water column and sediments, all of the above factors were taken into account. The net input or release of nitrogen within each of the three harbors was determined based upon the measured total dissolved nitrogen uptake or release, and estimate of particulate nitrogen input.

Sediment sampling was conducted throughout the primary component basins (Town Cove, Nauset Marsh) as well as tributary sub-basins (Wood Cove, Mill Pond, Salt Pond, Nauset Bay) of the overall system in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores in the system 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 (Section 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 Nauset Estuary were comparable to other similar embayments with similar configuration and flushing rates in southeastern Massachusetts. In addition to the measured rates, the pattern of sediment N release was similar to other systems, with the salt marsh basins and creeks ranging from low rates of release to net nitrogen uptake (Nauset Bay, -15.0 mg N m^{-2} d^{-1}; Salt Pond Bay, 26.6 mg N m^{-2} d^{-1}; Nauset Marsh, 8.4-29.9 mg N m^{-2} d^{-1}), the deeper semi-enclosed depositional basins showing moderate to high rates of net nitrogen release (Town Cove 64.4 mg N m^{-2} $d^{-1;}$ Salt Pond, 73.2 mg N m^{-2} d^{-1}; Wood Cove, 52.6 mg N m^{-2} d^{-1}'; Mill Pond, 24.1 mg N m^{-2} d^{-1}) and the shallow outer areas with oxidized sediments showing low to no net uptake (Town Cove Outer, -18.8 mg N m^{-2} d^{-1}; Mill Pond Outer -0.02 mg N m^{-2} d^{-1}).

The salt marsh basin of Nauset Bay was nearly identical to other salt marsh basins, such as Mill Creek (tributary to Lewis Bay), Lewis Pond (Parkers River) and Scudder Bay (Centerville River), -14.3 mg N m^{-2} d^{-1}, -11.8 mg N m^{-2} d^{-1} and -13.2 mg N m^{-2} d^{-1}, respectively. The Nauset Marsh creeks (8.4 to 29.9 mg N m^{-2} d^{-1}) were also similar to other similarly configured large tidal marsh creeks on Cape Cod. For example the marsh channel associated with lower Bass River, 20.1 mg N m^{-2}- d^{-1}, upper Parkers River, 39.9 mg N m^{-2} d^{-1}, and Back River marsh channels, 6.5 to 22.1 mg N m^{-2} d^{-1} all show comparable rates. The finding of higher rates of summer nitrogen release in smaller semi enclosed basins is common in Cape Cod estuaries. For example Rock Harbor, Orleans, showed moderate/high rates of nitrogen release, 80.8 mg N m^{-2} d^{-1}, similar to the Pleasant Bay sub-basins of Meetinghouse Pond, Areys Pond, Paw Wah Pond, 79.5, 107.3, 120.7 mg N m^{-2} d^{-1}, respectively. Finally, the relatively low rates of nitrogen exchange in the shallow open areas of Town Cove and Mill Pond were comparable to the more open areas of Pleasant Bay and Lewis Bay with oxidized sediments, -1.1 to 16.0 mg N m^{-2},and -1.1 to 16.0 mg N m^{-2} d^{-1}, respectively. The similarity in the pattern and rate of sediment nitrogen release throughout the Nauset Estuary compared to other comparable systems on Cape Cod, further supports the use of these measurements in the water quality modeling effort (Section VI).

Net nitrogen release rates for use in the water quality modeling effort for the main basins and sub-embayments of the Nauset Estuary system are presented in Table IV-6. The clear spatial pattern of sediment nitrogen flux also follows the pattern or sediment distribution, with depositional areas showing high rates of release and oxidized low organic sediments showing low rates of release. The sediments within the Nauset Estuary showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to this system and its flushing rate.

Table IV-6. Rates of net nitrogen return from sediments to the overlying waters of the Nauset Estuarine System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Section VI). Measurements represent July -August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			i.d. *
	Mean	S.E.	# sites	
Nauset Estuarine System				
Nauset Marsh - North	29.9	46.6	3	4-6
Nauset Marsh - South	8.4	3.7	5	7,8,20,21,24
Nauset Bay	-15.0	53.5	2	27,28
Salt Pond Bay	26.6	26.9	3	1-3
Salt Pond	73.2	0.6	2	25,26
Wood Cove	52.6	7.3	2	22,23
Mill Pond - Outer Basin	-0.02	7.0	2	31,32
Mill Pond - Inner Basin	24.1	55.1	2	29,30
Town Cove - Outer	-18.8	6.2	2	18,19
Town Cove - Inner	64.4	13.8	9	9-17

* Station numbers refer to Figure IV-7.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

The Nauset Harbor estuary system is within the boundaries of the Towns of Eastham and Orleans, Massachusetts, on the Atlantic shoreline of Cape Cod. A topographic map (Figure V-1) shows the general study area. Most of Nauset Harbor is moderately shallow with some deeper areas found in the associated sub-embayments of Salt Pond, Mill Pond and Town Cove. Circulation in the Harbor is dominated by tidal exchange with the open Atlantic Ocean.

The overall hydrodynamic study of the Nauset Harbor system proceeded as two component efforts. In the first portion of the study, bathymetry and tide 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 Nauset Harbor was performed to determine the variation of embayment depths throughout the system. This survey addressed the previous lack of adequate bathymetry data for this area. In addition to the bathymetry survey, tides were recorded at five stations for a month-long period. These tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of Nauset Harbor and its attached sub-embayments was developed in the second portion of this study. Using the bathymetry survey data, a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data from offshore of the harbor were used to define the open boundary condition that drives the circulation of the model while data measured within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the actual system. In addition to the tide data, ADCP velocity data from the October 31, 2001 survey in Nauset Harbor was processed to provide an independent means of verifying the performance of the Nauset system model.

V.2 DATA COLLECTION AND ANALYSIS

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

V.2.1 Bathymetry Data

Bathymetric data were collected in Nauset Harbor on October 30, 2001. The surveys employed an Odem HydroTrac fathometer mounted on a 16 ft motorized skiff. Positioning data were collected using a differential GPS. The position data from the GPS and the depth data from the fathometer were recorded digitally in real time using the Hypack hydrographic survey software package. Where practical, predetermined survey transects were followed at regular intervals. The actual survey paths are shown in Figure V-2. Collected bathymetry data were tide-corrected, to account for the change in water depths as the tide level changed during the survey period. The tide-correction was performed using tide data collected during the time of the survey.

Figure V-1. Detail of topographic map of the Nauset Harbor system.

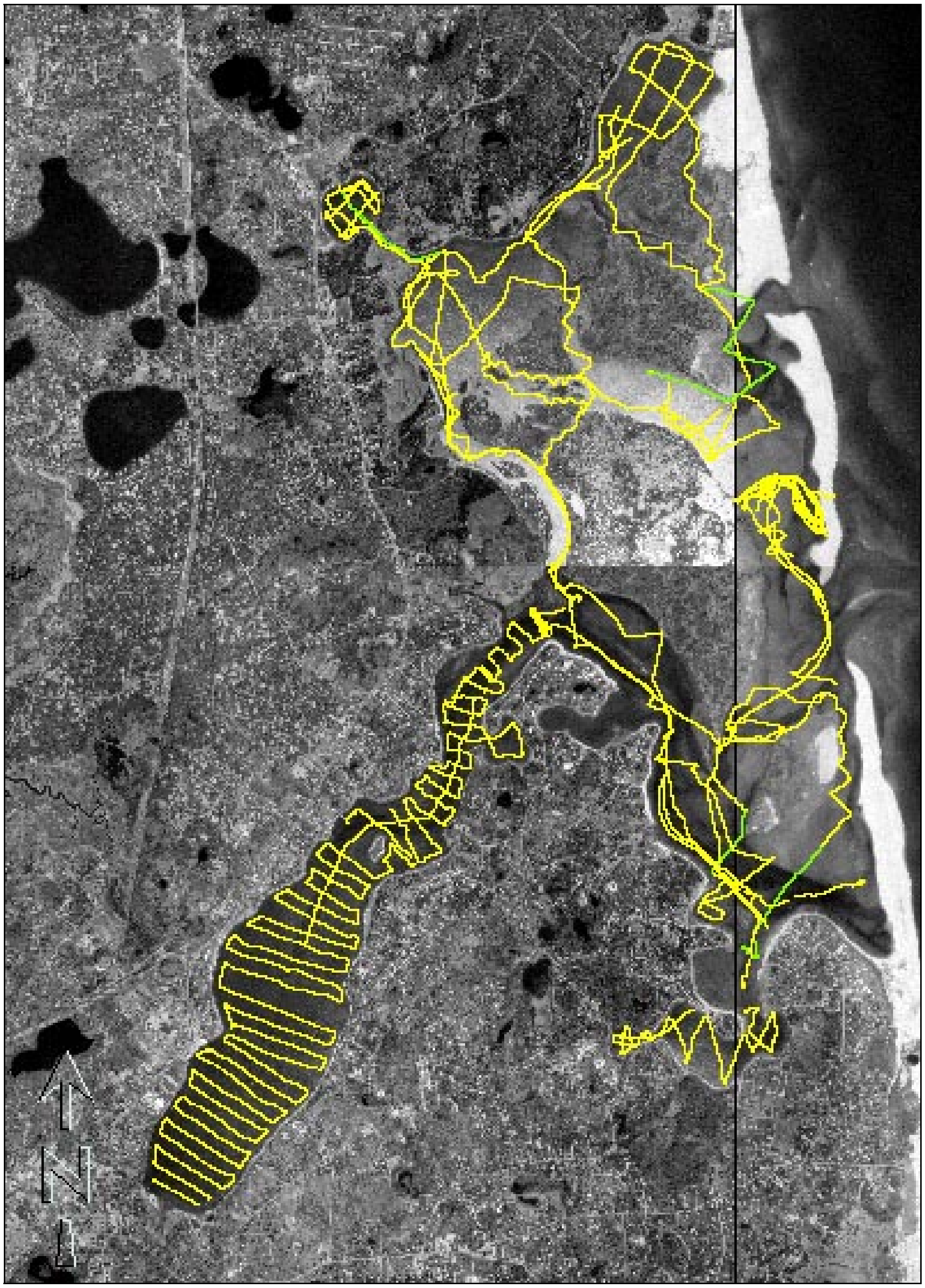


Figure V-2. Actual paths followed by survey boat during recent (Fall, 2001) bathymetry surveying of the Nauset Harbor system. Fathometer paths are plotted on a composite 1994 aerial photograph of the area.

V.2.2 Tide Data Collection and Analysis

Tide data were collected for this study in the fall of 2001 at stations positioned throughout the Nauset Harbor system. Tide data were collected by Temperature Depth Recorders (TDR), which are strain-gauge instruments that record pressure and ambient temperature. Each gauge was leveled to a standard survey vertical datum (NGVD 29).

The instruments deployed in this study were set to record data at 10-minute intervals for at least a 29-day period. This period of time is necessary to capture the bi-monthly variation between the spring and neap ranges of the tides observed in Orleans embayments. A 29-day tide record length is required to differentiate the several individual tidal constituents that make up the total observed tide. Tidal constituent determination is an ancillary analysis, which provides useful insight into the dynamics of an estuary. Typically, a shorter tide data record is used to run and calibrate hydrodynamic models, which is the primary purpose of collecting this data. A secondary purpose for the tide data, as mentioned previously, is to tide-correct bathymetry data, so that it can be referenced to some standard datum (e.g., NGVD 29).

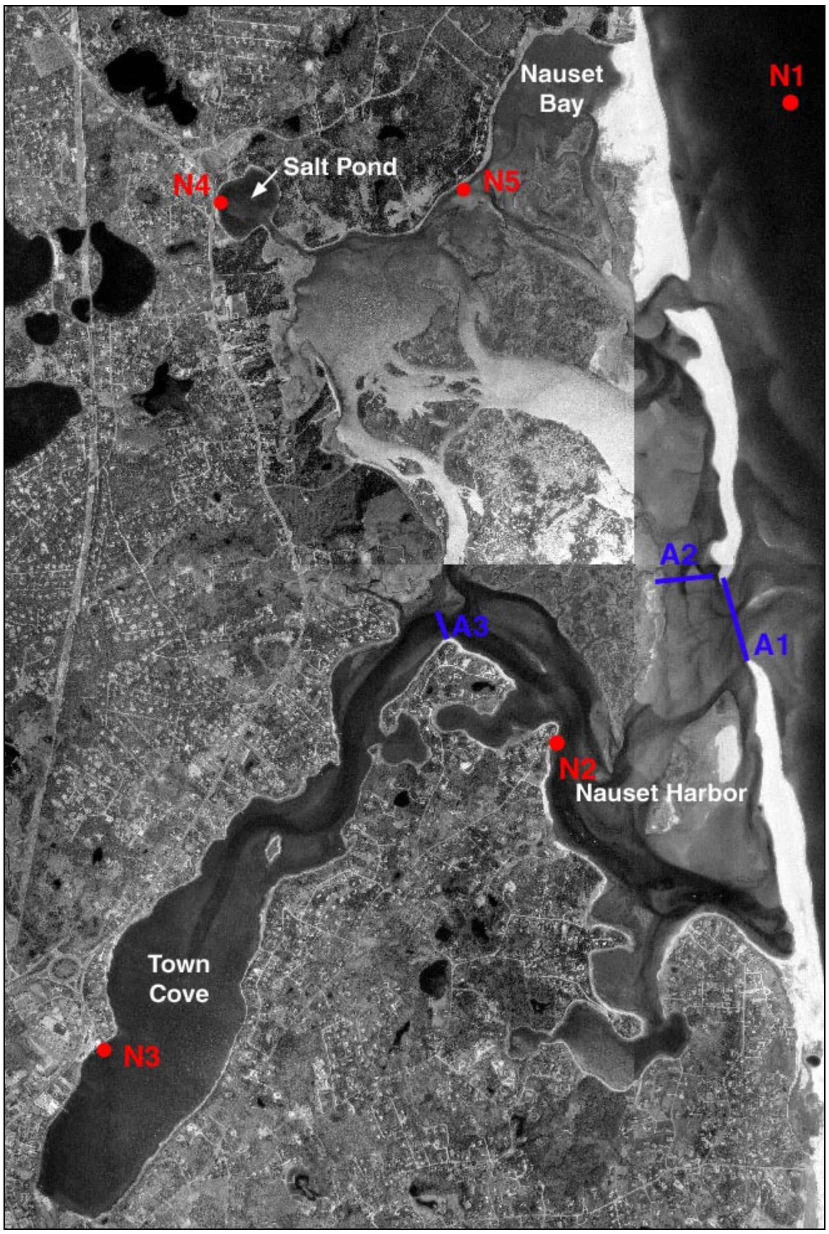


Figure V-3. Tide gauge locations for the Nauset Harbor system (red), offshore the National Seashore (N1), at Nauset Harbor (N2), Town Cove (N3), Salt Pond (N4), and Nauset Bay (N5). ADCP transects, followed during the survey of tidal currents, are shown as blue lines.

The deployment locations of each of the gauges are shown in Figure V-3. Tides at five locations were measured in the Nauset Harbor system, from late September 2001 when the offshore gauges were deployed, to mid-November 2001 when the last gauge in Nauset Bay was recovered. Tides were measured offshore the system inlet, and inside the system at Nauset Harbor, Town Cove, Salt Pond, and Nauset Bay. Professional divers were used to deploy the two offshore gauges in deep water outside the inlet to Nauset Harbor. These gauges were fixed to a frame lowered onto the seafloor. The other four gauges inside the system were deployed by Applied Coastal personnel and were affixed to either permanent pilings (e.g., Town Cove gauge), or to screw anchors temporarily placed on the bottom (e.g., Nauset Bay).

The complete tide data record from each of the different gauge deployments is presented in Figure V-4. From the gauges deployed in this present study, only one gauge malfunctioned, causing a partial loss of data. The problem gauge was deployed in Nauset Harbor, between Town Cove and the system inlet. The gauge failure was caused by the build-up of corrosion by-products in the pressure sensor port of the instrument, which is not a typical mode of failure for the particular gauge employed at this location. Though the TDR data record does not extend to the desired 29-day length, it is still useful for calibrating the hydrodynamic model of the Nauset Bay system, which was the primary purpose of collecting these data.

A shorter time interval was extracted from the 29 day TDR records from the Nauset Harbor system gauges and shown in Figures V-5. These two plots demonstrate in a simple way how the offshore tide signal is attenuated as it propagates though the Nauset Harbor system. The loss of amplitude with distance from the inlet of an estuary is described as tidal attenuation.

A 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 each component of the overall system relative to tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each component of the system.

The harmonic analysis was performed on the time series data from each gauge location. The results of this analysis are presented in Table V-1. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 known tidal constituents result from this procedure. 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-6.

Table V-1 presents the amplitudes of eight tidal constituents for each gauge location in the Nauset Harbor system. The M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the tide signal at all of the gauge deployment locations. The total range of the M_2 tide is twice the amplitude, e.g., 6.61 feet for the tide offshore of Nauset Harbor. The K_1 and O_1 constituents represent diurnal tides that occur once daily.

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 that are typically each about 10% of the total observed tide. The M_{sf} is a lunar-solar fortnightly constituent with a period of approximately 14 days, and is the result of the periodic conjunction of the sun and moon. 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 offshore amplitudes of both the M_4 and M_6 are 0.01 ft, but inside the system these constituents are much larger.

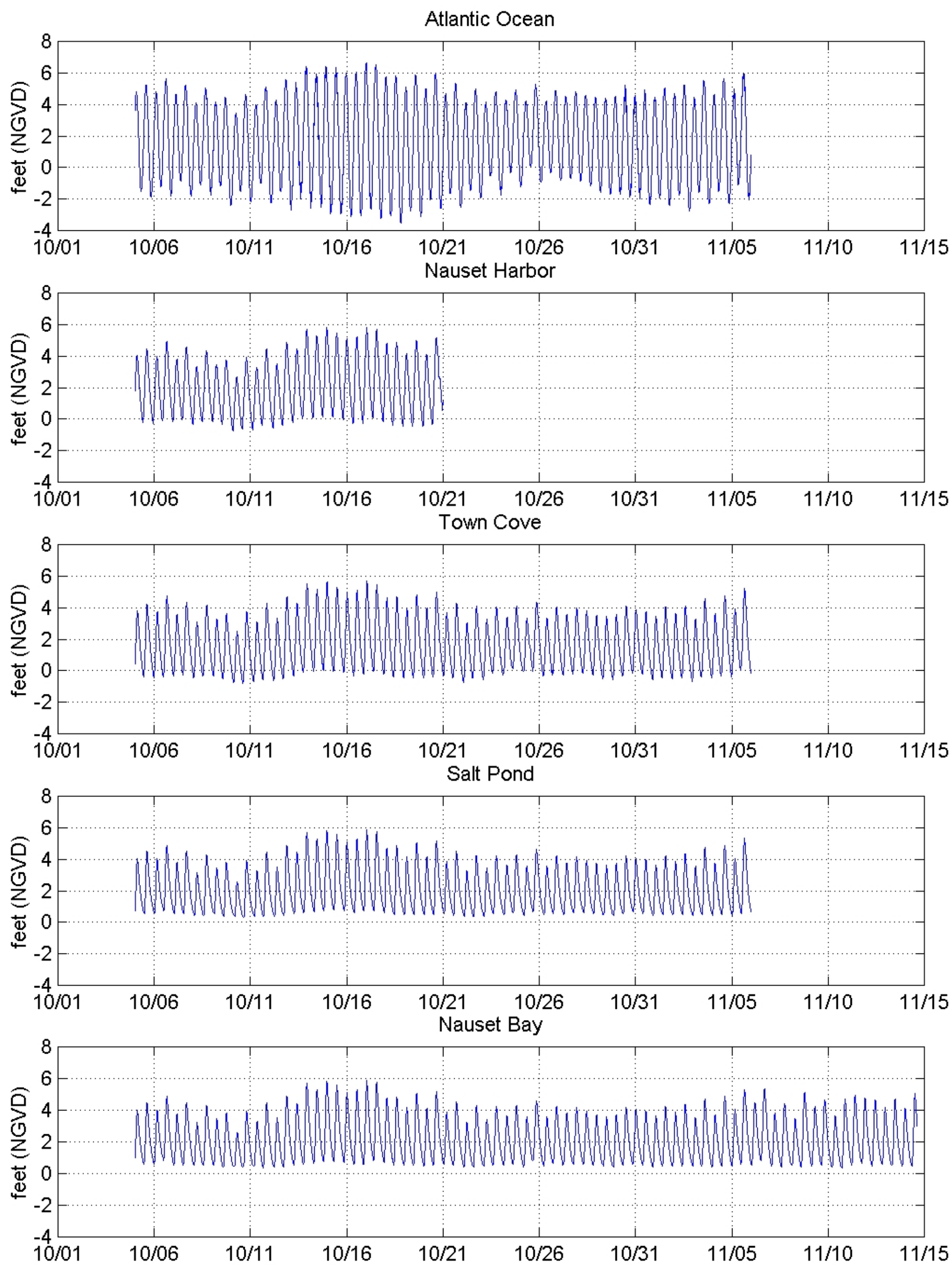


Figure V-4. Complete TDR records for gauges deployed in the Nauset Harbor system during the fall of 2001.

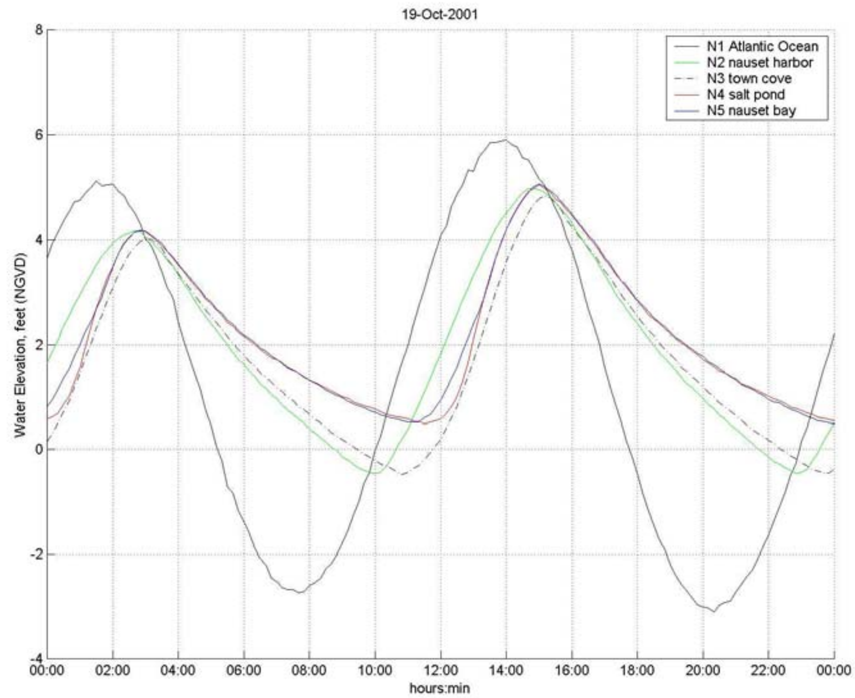


Figure V-5. Close-up of TDR records of tides as measured throughout the Nauset Harbor system. From this plot, it is evident that significant tidal attenuation occurs as a result of flow restrictions present at the inlet to the system. The tidal attenuation is seen as a reduction in amplitude (range) and also as a phase shift (time lag) when compared to the offshore signal.

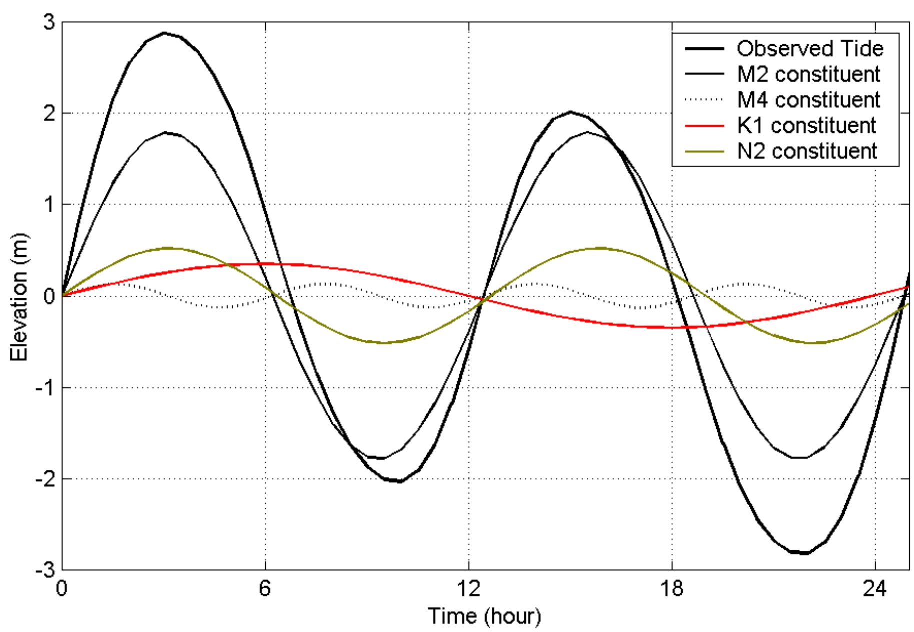


Figure V-6. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-1. Major tidal constituents determined for gauge locations in the Nauset Harbor system, for the time period October 5 through November 6, 2001.

	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
Offshore Nauset Harbor	3.31	0.01	0.01	0.60	0.79	0.35	0.37	0.12
Nauset Bay	1.59	0.42	0.09	0.20	0.33	0.25	0.24	0.15
Salt Pond	1.59	0.50	0.14	0.19	0.34	0.25	0.24	0.21
Town Cove	1.91	0.43	0.06	0.23	0.37	0.26	0.25	0.20

Data in Table V-1 show how the constituents vary as the tide propagates into the upper reaches of the system. Note the reduction in the M_2 amplitude between the inlet and Salt Pond and Town Cove, in the Nauset Harbor System. Frictional damping is evident as a decrease in the amplitude of M_2 constituent. A portion of the energy lost from the M_2 tide is transferred to higher harmonics (i.e., the M_4 and M_6), and is observed as an increase in amplitude of these constituents over the length of an estuary, as is evident in the data from this system.

As discussed previously, phase delay is another indication of tidal damping and is manifest as a later high tide at inland locations. The greater the frictional effects, the longer the delay between locations. As an example of this effect, the phase delay of the M_2 tide at Nauset Bay compared to the offshore gauge deployed east of Nauset Inlet was determined to be 113 minutes by the harmonic analysis. For Salt Pond the phase delay of the M_2 tide was determined to be 123 minutes from the offshore gauge, or an additional 10 minutes delay from Nauset Bay. In Town Cove, the phase lag is 117 minutes from offshore. The large phase delays result from the substantial tide attenuation that occurs at the inlet to the system.

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 Nauset Harbor is presented in Table V-2 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 in the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from the Atlantic Ocean with the computed astronomical tide resulting from the harmonic analysis and the resulting non-tidal residual. This residual signal analysis shows that water level changes in the Nauset Harbor system are predominantly due to astronomical tides. Salt Pond has the largest residual, though the astronomical tide accounts for more than 92% of the variance observed in water level data at this specific interior location.

Table V-2. Percentages of Tidal versus Non-Tidal Energy for Nauset Harbor embayments.			
TDR Location	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Offshore Nauset Harbor	6.04	98.6	1.4
Nauset Bay	1.58	93.5	6.5
Salt Pond	1.58	92.8	7.2
Nauset Harbor	2.61	97.1	2.9
Town Cove	2.12	94.8	5.2

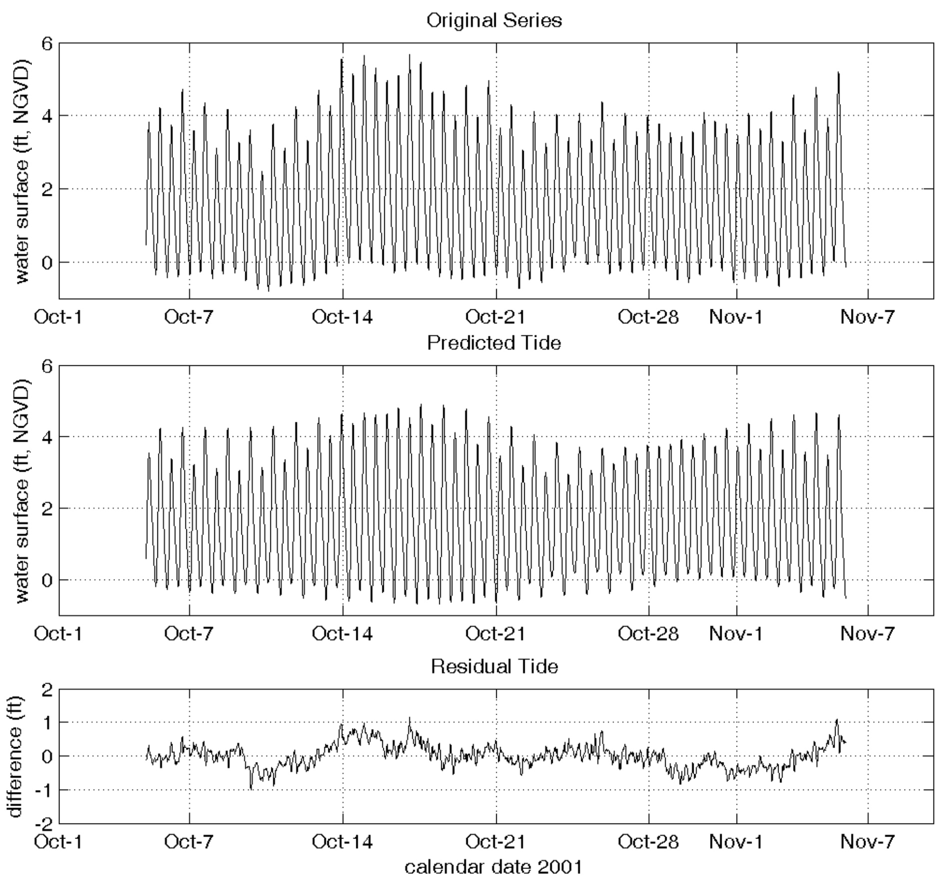


Figure V-7. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 23 individual tide constituents determine in the harmonic analysis of the Town Cove gauge data. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (r=m-p).

V.2.1 ADCP Data Analysis

Cross-channel current measurements were surveyed through a tidal cycle in the Nauset Harbor system on October 31, 2001 to resolve spatial and temporal variations in tidal current patterns. The survey was designed to observe tidal flow through the Nauset inlet and how the flow was divided into Nauset Bay and Town Cove at hourly intervals. Figures V-8 through V-11 show color contours of the current measurements observed during the flood and ebb tide cycles at each of the three transects surveyed at strategic points in the overall system. 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, at the Nauset inlet, positive along-channel flow is to the west-southwest, and positive cross-channel flow is moving to the north-northwest. In Figure V-8 the lower left panel of the figure shows the depth-averaged currents across the channel as projected on a 1994 aerial photograph of the inlet. It should be noted that the 1994 aerial shows the inlet in a different position than it presently is. The lower right panel indicates the stage of the tide at the time that the ADCP survey was taken. The tidal stage is marked in the figure by a vertical line through the water elevation curve.

The complex geometry of Nauset Inlet results in an unequal distribution of currents across the entrance. During flood tide, currents were evenly distributed through the inlet channel in a divergent pattern (Figure V-8), where currents near the northern limit of the inlet flowing more to the west, and currents near the southern limit of the inlet flowing more to the south. Peak velocities during the flood tide at the inlet were 3.5 ft/sec. The maximum flooding flow rate through Nauset Inlet was computer to be 15,400 ft^3/sec. During the following ebb tide (Figure V-9), the flow pattern is convergent just inside the inlet, as water drains from Nauset Bay to the north, and Nauset Harbor to the south. Maximum ebb currents measured by the ADCP were 4.5 ft/sec. The maximum ebb flow rate out of the inlet was computed to be –12,200 ft^3/sec.

The flows across the Town Cove transect (inside the Nauset Harbor system) were less convergent/divergent than flows at the inlet transect (Figure V-10). Velocities across the entrance to Town Cove were more easily measured than at the inlet. The conditions were much more favorable for navigating the small boat from which the ADCP was deployed, compared to the area near the system inlet, which was exposed to ocean waves, and had much swifter currents. Peak measured flow rates at the entrance to Town Cove were 2.0 ft/sec during the flood tide, and 1.9 ft/sec during the ebb tide (Figure V-11). The maximum computed flood flow rate at this transect was computed to be 5,800 ft^3/sec, verses the maximum ebb flow rate of 3,600 ft^3/sec.

At both Nauset Harbor transects, maximum computed flood tide flow rates were greater than ebb tide flow rates. Ebb flow rates were typically 20 to 40 percent less than flood flow rates. The difference between ebb and flood tides is due to the duration of the ebb and flood phases of the tide cycle. Inside the Nauset Harbor system the flood phase has a duration of approximately 4.4 hours, and the ebb phase has a longer duration of nearly 8 hours. Because the ebb tide has a longer duration, flow rates are less than during the flood tide. This is an indication that the system is flood dominant, and would therefore tend to be a net importer of sediment. This is a typical characteristic of marsh systems.

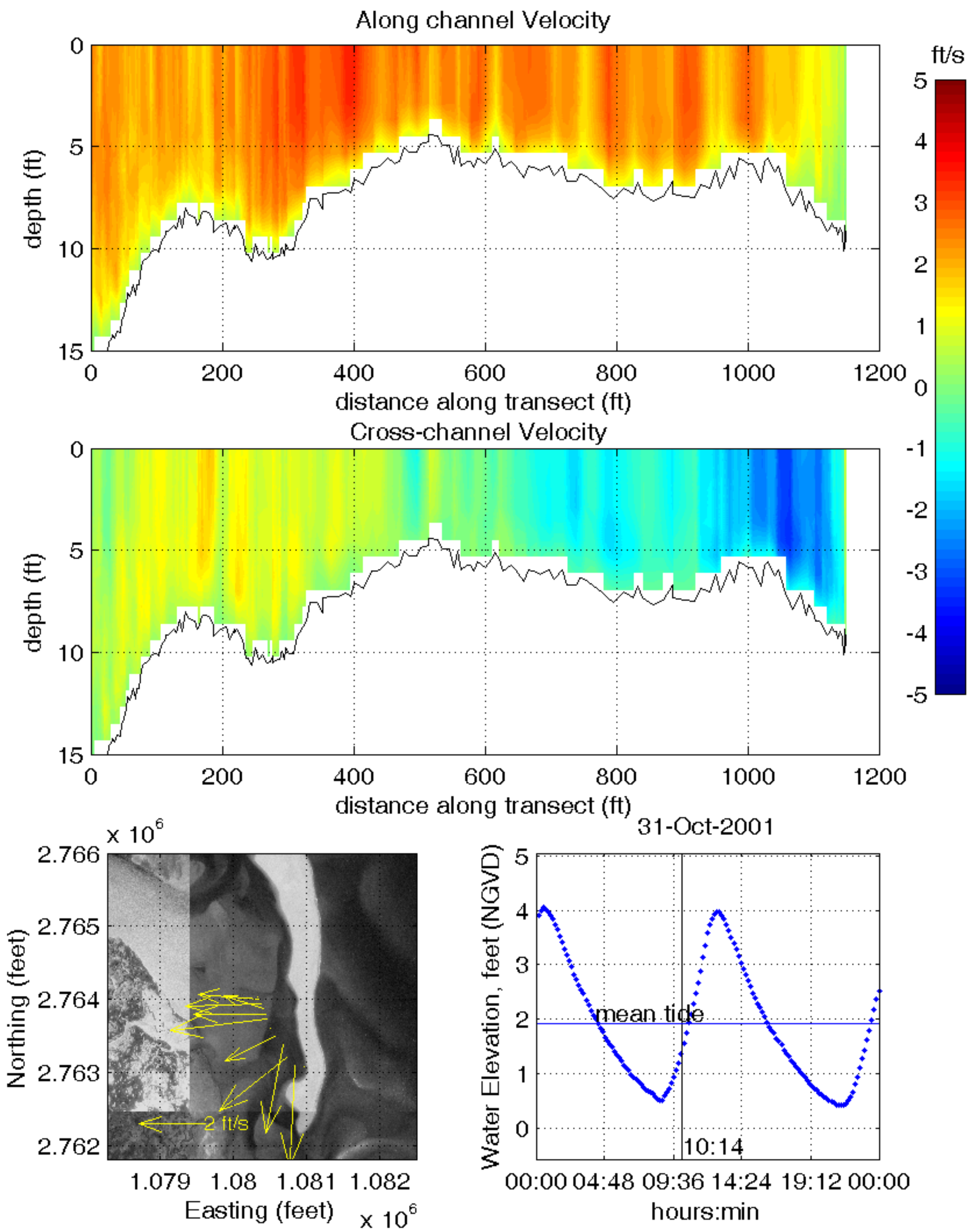


Figure V-8. Color contour plots of along-channel and cross-channel velocity components for transect line run north-to-south across Nauset inlet measured at 10:14 on October 31, 2001 during a flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive 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 of the survey area. A plot of tide for the survey day is also given.

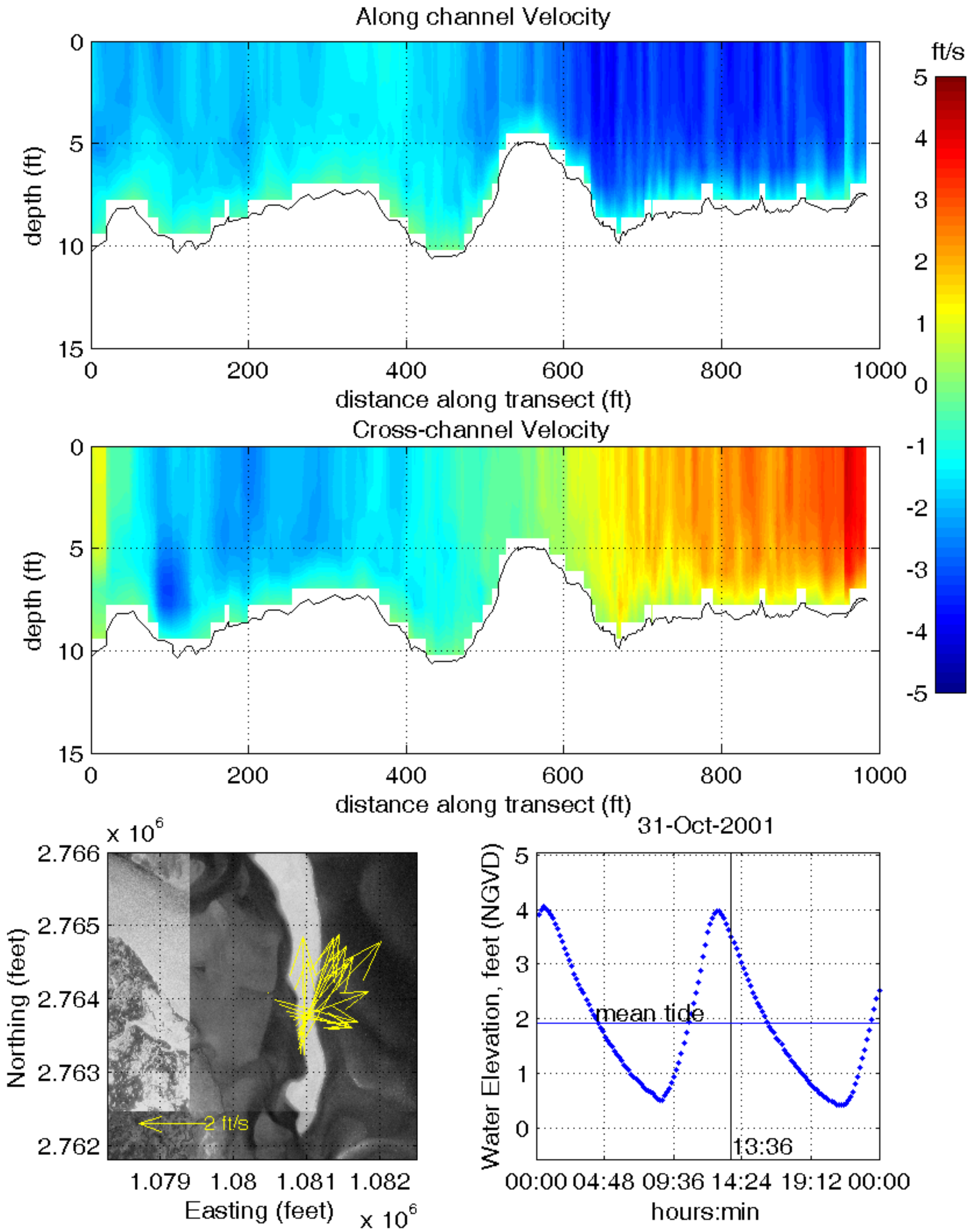


Figure V-9. Color contour plots of along-channel and cross-channel velocity components for transect line run north-to-south across Nauset inlet measured at 13:36 on October 31, 2001 during an ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive 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 of the survey area. A plot of tide for the survey day is also given.

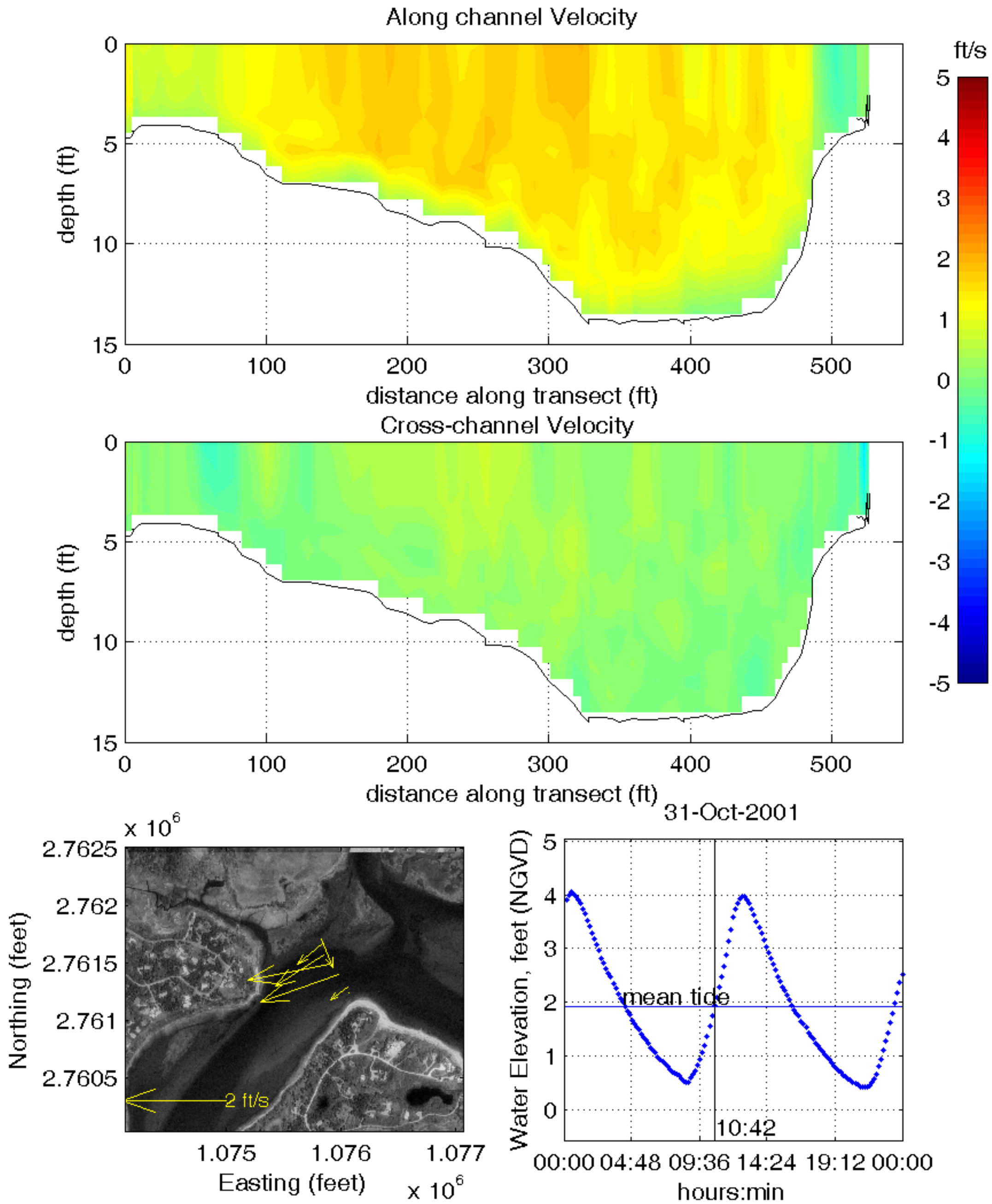


Figure V-10. Color contour plots of along-channel and cross-channel velocity components for transect line run southeast-to-northwest across the entrance to Town Cove, measured at 10:42 on October 31, 2001 during a flooding tide. Positive along-channel currents (top panel) indicate the flow is moving 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 of the survey area. A plot of tide for the survey day is also given.

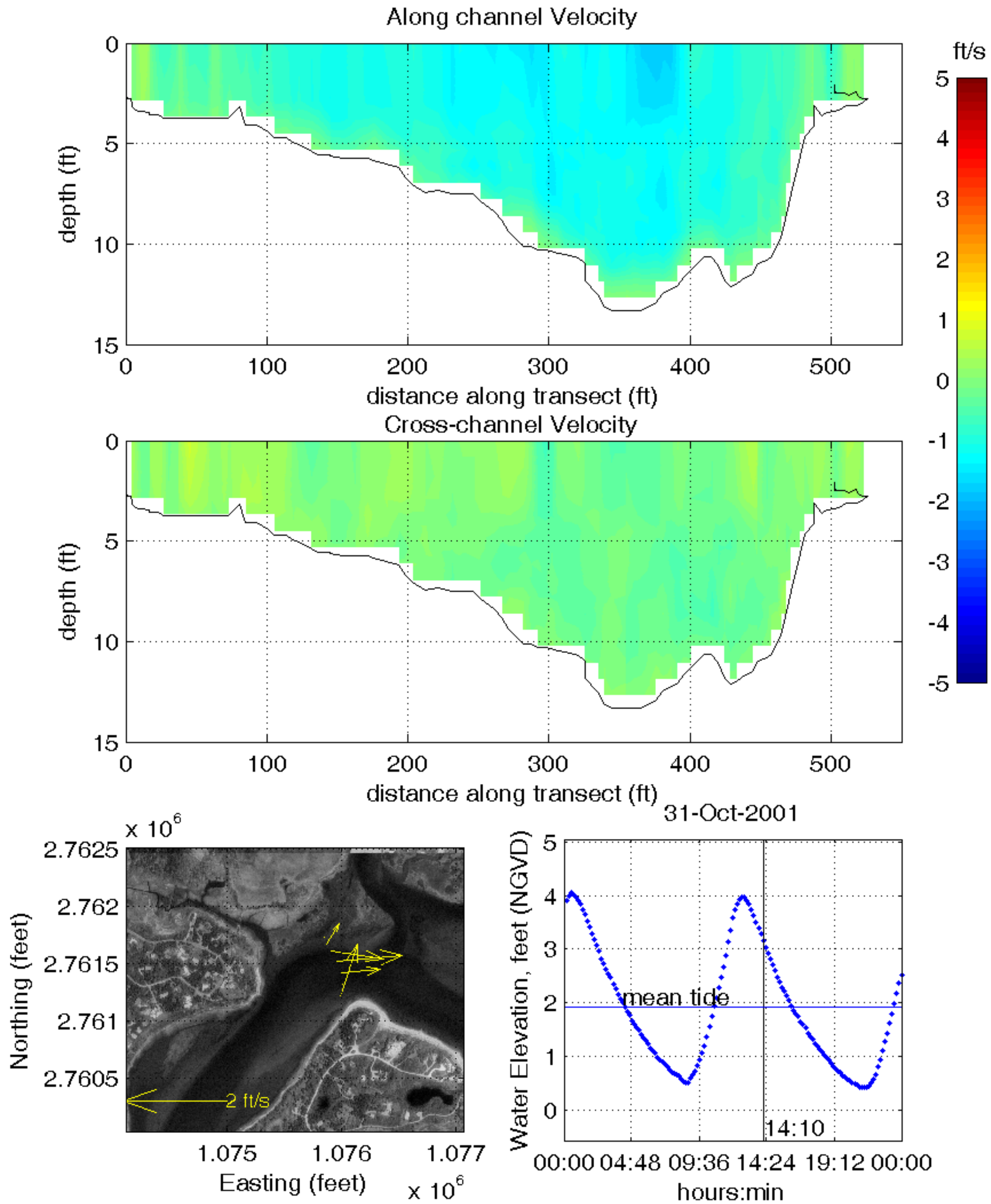


Figure V-11. Color contour plots of along-channel and cross-channel velocity components for transect line run southeast-to-northwest across the entrance to Town Cove, measured at 14:10 on October 31, 2001 during an ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into 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 of the survey area. A plot of tide for the survey day is also given.

V.3 HYDRODYNAMIC MODELING

For the Nauset Harbor estuary system, Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing. The model code 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 and rivers. Applied Coastal staff members have utilized RMA-2 for numerous flushing studies on Cape Cod, including West Falmouth Harbor, Popponesset Bay, Chatham embayments (Kelley, *et al*, 2001), Falmouth "finger" Ponds (Ramsey, *et al*, 2000), and Barnstable Harbor (Wood, *et al*, 1999).

V.3.1 Model Theory

In its original form, RMA-2 was developed by William Norton and Ian King under contract to 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 researcher through a package called the Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report were primarily generated within the SMS modeling package.

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

The extent of the finite element grid was generated using 1994 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of the system based on the tide gauge data collected offshore Nauset Beach. Once grid and boundary conditions were set, the model was calibrated to ensure that the computer model accurately represents the tidal dynamics of the real physical system. Various friction and eddy viscosity coefficients were adjusted through several (20+) model calibration simulations for the system to ultimately obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for subsequent detailed water quality modeling.

V.3.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. A 1994 digital aerial orthophoto and recent bathymetry survey data were imported to SMS to facilitate the construction of a finite element grid to represent each component of the modeled estuary. The aerial photographs were used to determine the land boundary of the system, as well as determine the surface coverage of salt marsh resources. The completed grid meshes for the Nauset Harbor systems are shown in Figure V-12. Bathymetry data were interpolated to the developed finite element mesh as seen in Figure V-13.

The finite element grid for the system provides the detail necessary to accurately evaluate the variation of hydrodynamic properties for the components of the modeled embayment. Areas of marsh were included in the model because they represent a large portion of the total area of this system and have a significant effect on system hydrodynamics. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the modeled 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 marsh creeks and channels was designed to provide a more detailed analysis in these regions of rapidly varying flow. Widely spaced nodes were often employed in areas where flow patterns are not likely to change dramatically, such as in Town Cove and on the upper reaches of the modeled marsh plain. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

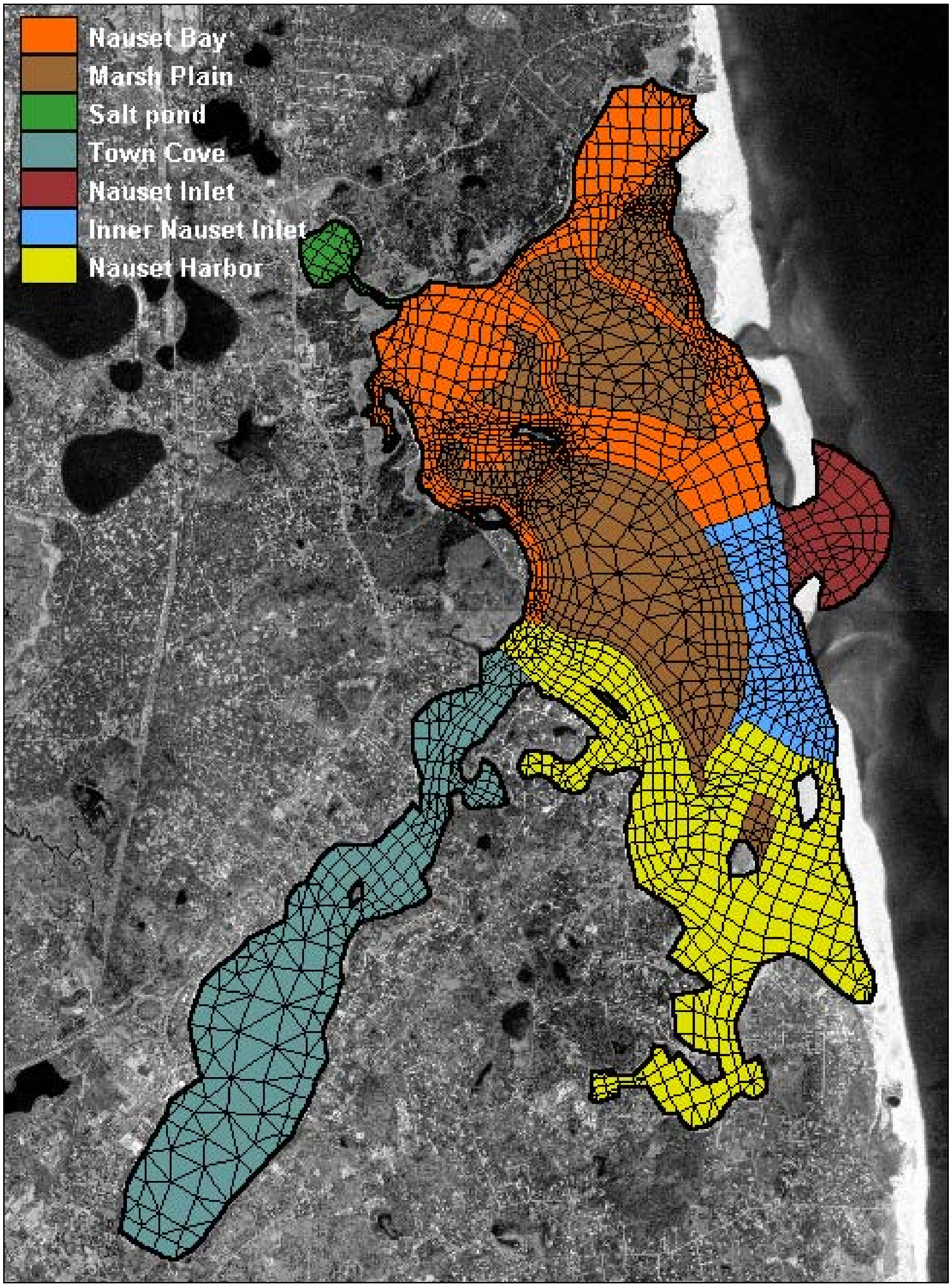


Figure V-12. Plot of numerical grid used for hydrodynamic modeling of the Nauset Harbor system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for individual sub-embayments.

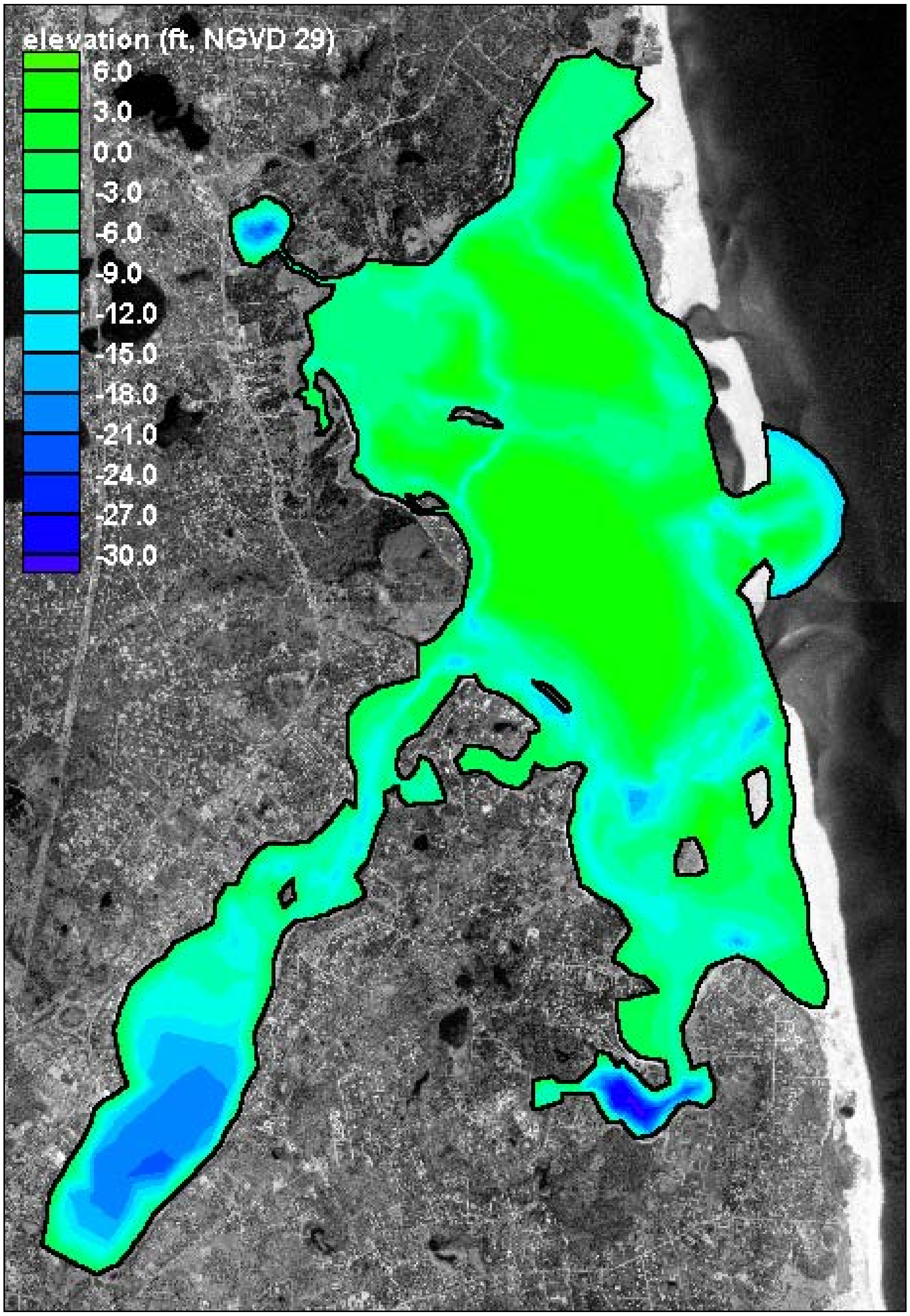


Figure V-13. Depth contour plot of the numerical grid for Nauset Harbor showing 3-foot contour intervals relative to NGVD29.

V.3.2.2 Boundary condition specification

Two types of boundary conditions were employed for the RMA-2 model of the Nauset Harbor embayment: 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.

A tidal elevation boundary condition was specified at the inlet. TDR measured tide data collected offshore Nauset Harbor provided the required data. The rise and fall of the tide at this location is the primary driving force for estuarine circulation in the model. Dynamic (time-varying) model simulations specified a new water surface elevation at the model open boundary every model time step (10 minutes). The model time step selected corresponded to the time step of the tide data record, i.e., a 10 minute time step.

V.3.2.3 Calibration

After developing the finite element grids and specifying boundary conditions, the model for the Nauset Harbor embayment system was calibrated. The calibration procedure ensures that the model accurately predicts tidal stages and flows as observed through the field measurement program. Numerous model simulations are required (typically 20+) to calibrate an estuary model, specifying a range of friction and eddy viscosity coefficients during the calibration procedure.

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, an approximate five-day period (10 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed previously in the data collection section (Section V.2.2). 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 phase (time) lag and amplitude (height) damping of dominant tidal constituents

For the Nauset Harbor system, the calibration was performed for a five-day period beginning October 13, 2001 at 0900 EST. This representative time period included the spring tide range of conditions, where the tide range and tidal currents are greatest.

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). For The Nauset Harbor system, the verification run used a period of 7.25 days (14 tide cycles) beginning October 24, 2001, at 1830 EST.

The calibrated models were used to analyze existing detailed flow patterns and compute embayment 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 over the entire seven-day simulation period. 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.

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a characteristic of the channel roughness and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.02 and 0.07 were specified for all element material types. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels and marsh plains with higher friction (Henderson, 1966).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning's coefficients were matched to bottom type. For example, lower friction coefficients were specified for Town Cove, versus the marsh plain of the system which provides greater flow resistance. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based on ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992) 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-3.

Table V-3. Manning's Roughness coefficients used in simulations of modeled embayments. These embayment delineations correspond to the material type areas shown in Figures V-1.

System Embayment	Bottom Friction
Nauset Bay	0.040
Nauset Marsh Plain	0.070
Salt Pond	0.030
Town Cove	0.025
Nauset Inlet	0.040
Inner Nauset Inlet	0.035
Nauset Harbor	0.035

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 80 and 100 lb-sec/ft^2. Higher values (up to 200 lb-sec/ft^2) were used on the marsh plain, to ensure numerical stability.

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain included in the model. 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 initially rises within the channels and creeks until the 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 the point of 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 capacity of an element to hold water, like squeezing a sponge. The marsh porosity feature of RMA-2 is typically utilized in estuarine systems where the marsh plain has a significant impact on the hydrodynamics of a system, such as Nauset Harbor which includes extensive marsh resources.

A best-fit of model predictions for the TDR deployments was achieved using the aforementioned values for friction and turbulent exchange. Figures V-14 through V-18 illustrate the five-day calibration simulation along with 50-hour sub-section, for TDR locations throughout the Nauset Harbor. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

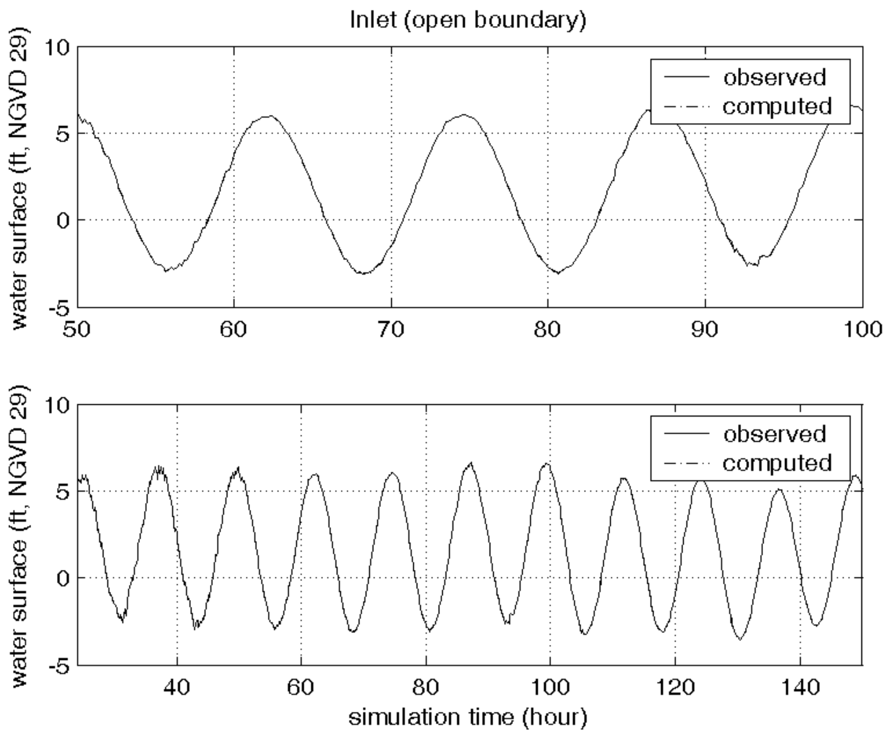


Figure V-14. Comparison of model output and measured tides for offshore Nauset Harbor, during model calibration time period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

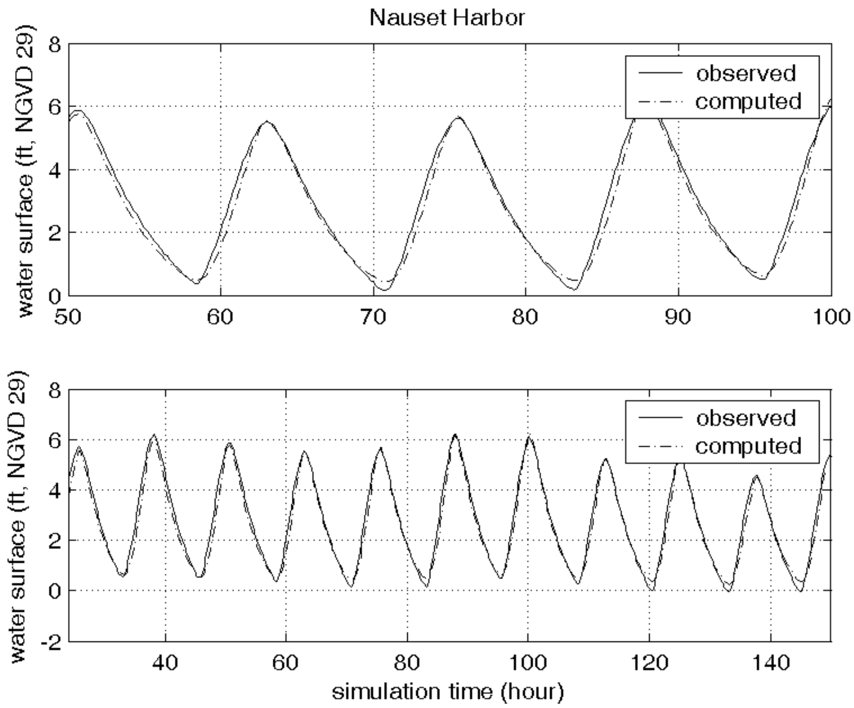


Figure V-15. Comparison of model output and measured tides for the TDR location in Nauset Harbor, during model calibration time period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

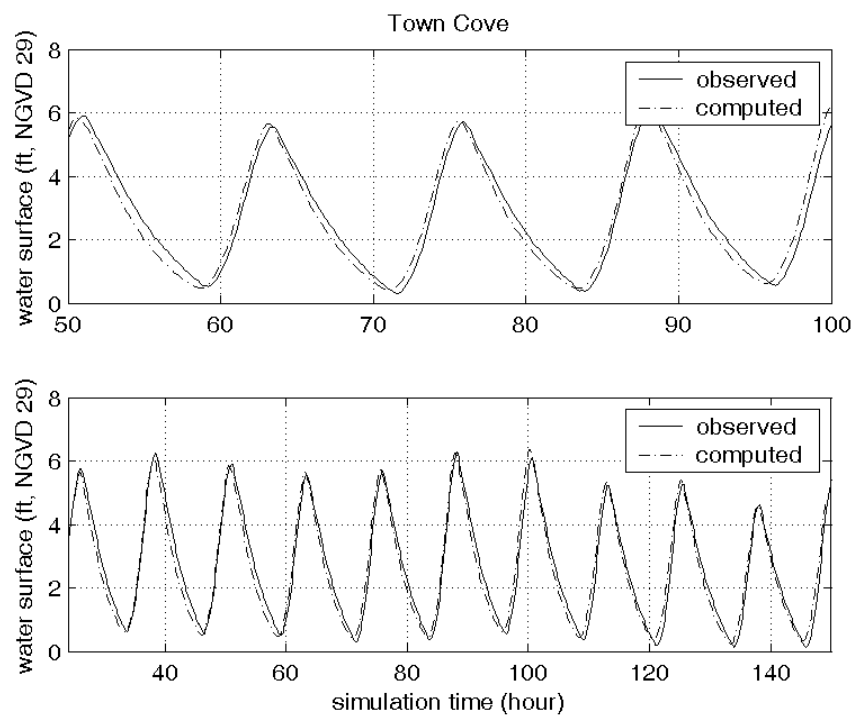


Figure V-16. Comparison of model output and measured tides for the TDR location in Town Cove (of the Nauset Harbor system), during model calibration time period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

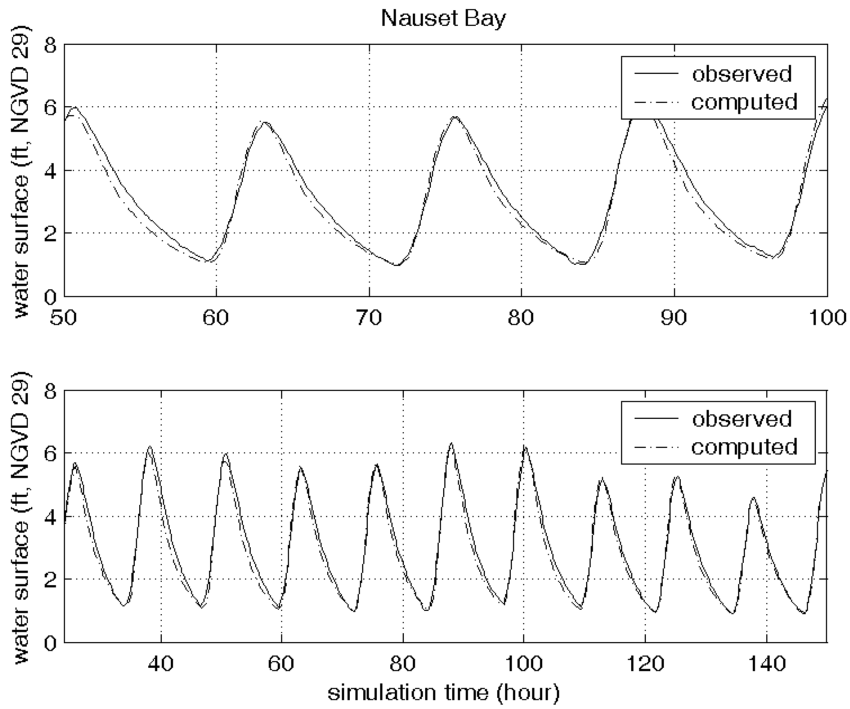


Figure V-17. Comparison of model output and measured tides for the TDR location in Nauset Bay (of the Nauset Harbor system), during model calibration time period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

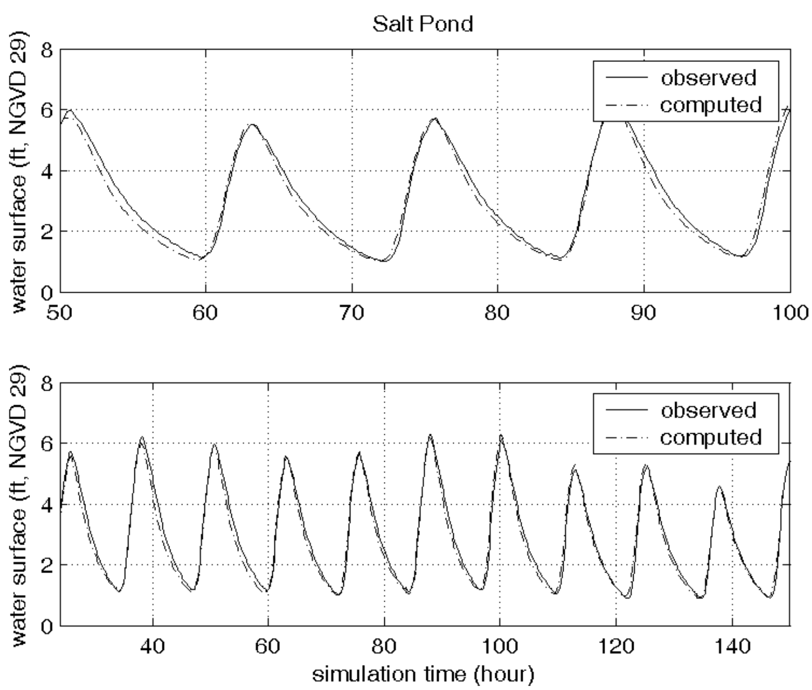


Figure V-18. Comparison of model output and measured tides for the TDR location in Salt Pond (of the Nauset Harbor system), during model calibration time period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

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 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled systems. Due to the duration of the model runs (approximately 5 days of simulated time) 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-4 for the calibration period differ from those shown previously in the data collection section of this chapter because constituents were computed for only the five-day section of the 38-days represented in Table V-1. Table V-4 compares tidal constituent height and phase 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.

The constituent calibration resulted in generally excellent agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.1 ft, which is of the same order of the accuracy of the tide gauges ($\pm$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.

The hydrodynamic model's ability to predict propagation of the secondary non-linear constituents through the estuary is important for understanding the attenuation of the tidal signal and the impact this has on estuarine circulation. Of primary interest is the M_4 constituent, which can be used to determine the flood dominance (sediment trapping characteristics) of an estuarine system. Proper prediction of M_4 provides confidence in the model's accuracy, since this indicates that the model is capable of simulating the tidal wave form and size. Similar to the model predictions for M_2, comparison of the information from Table V-4 indicates that the modeled phase of the M_4 generally falls within one time step of the observed value.

Table V-4. Tidal constituents for measured water level data and calibrated model output for Nauset Harbor, during model calibration time period .						
Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nauset Inlet*	4.455	0.013	0.014	0.151	27.8	-167.5
Nauset Harbor	2.315	0.557	0.085	0.114	71.2	93.2
Town Cove	2.321	0.619	0.125	0.114	76.0	101.0
Nauset Bay	1.971	0.734	0.229	0.107	78.8	107.0
Salt Pond	1.978	0.733	0.228	0.107	79.5	108.5
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nauset Inlet*	4.435	0.015	0.015	0.149	28.0	-172.0
Nauset Harbor	2.439	0.477	0.032	0.114	68.2	71.6
Town Cove	2.300	0.649	0.129	0.109	86.7	111.8
Nauset Bay	2.004	0.646	0.166	0.103	83.7	110.2
Salt Pond	1.998	0.708	0.236	0.107	85.3	114.9
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nauset Inlet*	-0.02	0.00	0.00	0.00	0.5	-4.7
Nauset Harbor	0.12	-0.08	-0.05	0.00	-6.2	-22.4
Town Cove	-0.02	0.03	0.00	0.00	22.1	11.2
Nauset Bay	0.03	-0.09	-0.06	0.00	10.0	3.3
Salt Pond	0.02	-0.03	0.01	0.00	12.0	6.6

*model open boundary

V.2.2.4 Model Verification

The calibration procedure used in the development of the finite-element model for the Nauset Harbor system required a match between measured and modeled tides. Additional model verification model runs were performed to verify the model performance during time periods different from the calibration time period. In this manner, the calibrated model is tested to ensure its accuracy when run for any time period outside the calibration period. The results of the model verification runs are shown in Table V-5. The analysis of the verification model runs in these tables shows that the model performs with a similar degree of accuracy to the calibration runs.

The selected verification time period was chosen so that it did not overlap with the original calibration period. For Nauset Harbor, the verification period began October 13, 2001 at 0900 EST, and included seven lunar days (24 hours, 50 minutes each) plus a 24 hour model run up period.

Table V-5. Tidal constituents for measured water level data and calibrated model output for Nauset Harbor, during model verification time period.

Location	Constituent Amplitude (ft)				Phase (deg)	
Model verification run						
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nauset Inlet*	2.96	0.02	0.01	0.03	29.2	116.6
Nauset Harbor	-	-	-	-	-	-
Town Cove	1.70	0.34	0.05	0.07	76.9	98.5
Nauset Bay	1.40	0.47	0.14	0.08	85.6	113.5
Salt Pond	1.41	0.47	0.13	0.08	86.0	114.7
Measured tide during verification period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nauset Inlet*	2.95	0.02	0.01	0.03	29.4	125.0
Nauset Harbor	-	-	-	-	-	-
Town Cove	1.82	0.40	0.05	0.08	84.9	104.1
Nauset Bay	1.49	0.41	0.09	0.09	86.3	113.1
Salt Pond	1.48	0.49	0.15	0.09	88.4	138.6
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nauset Inlet*	-0.01	0.00	0.00	0.00	0	9
Nauset Harbor	-	-	-	-	-	-
Town Cove	0.12	0.06	0.00	0.01	17	6
Nauset Bay	0.09	-0.06	-0.05	0.01	2	0
Salt Pond	0.07	0.02	0.02	0.01	5	4

*model open boundary

An additional model verification check was possible by using collected ADCP velocity data to verify the performance of the Nauset Harbor 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 earlier in section V.2.1. For the model verification, the Nauset Harbor model was run for the period covered during the ADCP survey on October 31, 2001. Model flow rates were computed in RMA-2 at continuity lines (channel cross-sections) that correspond to the actual ADCP transects followed in each survey (i.e., across the inlet and at the entrance to Town Cove).

Comparisons of the measured and computed volume flow rates in the Nauset Harbor system are shown in Figures V-19 and V-20. For each figure, the top plot shows the flow comparison, and the lower plot shows tide elevation for the same time 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 inlet, and in the harbor. 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.

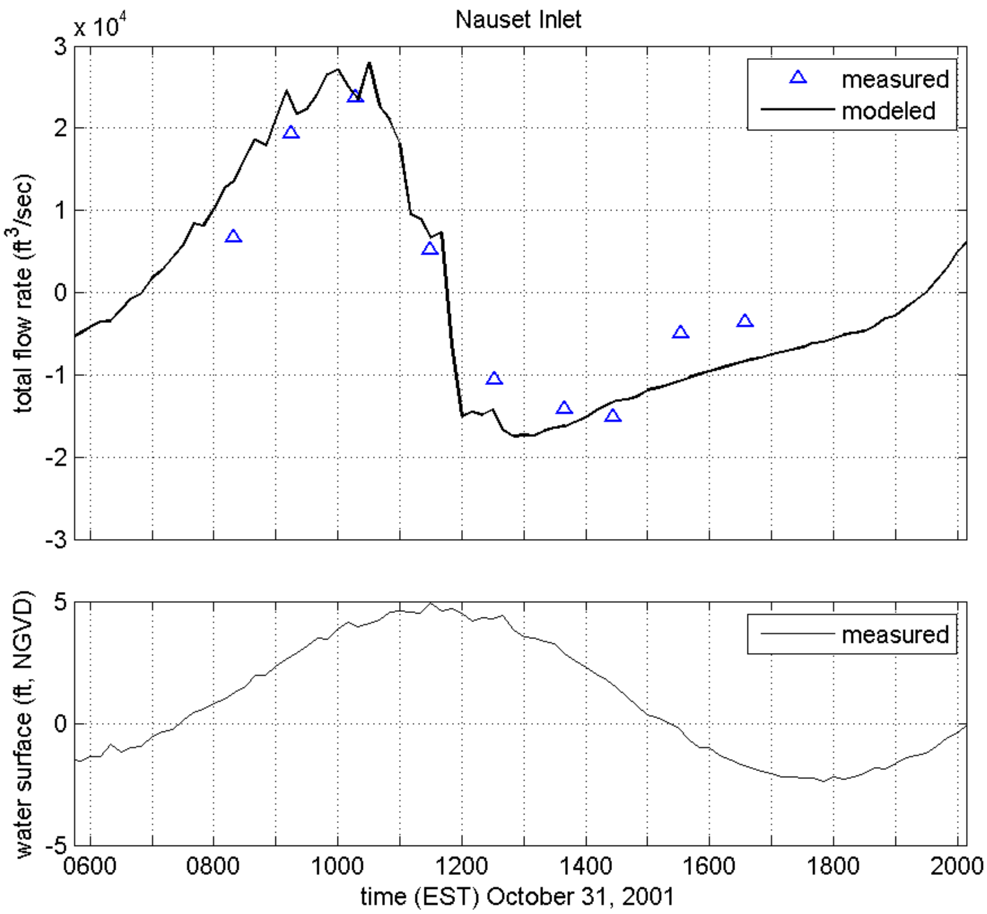


Figure V-19. Comparison of measured volume flow rates versus modeled flow rates (top plot) through Nauset Harbor Inlet over a tidal cycle on October 31, 2001. Flood flows into the pond are positive (+), and ebb flows out of the pond are negative (-). The bottom plot shows the tide elevation offshore of the Inlet. R^2 correlation of model and measurements is 0.77 and RMS error is computed to be 6,385 ft^3/sec.

Figure V-20 for the entrance to Town Cove shows exceptionally good agreement with the model predictions. The calibrated model accurately describes the magnitude of the discharge through into Town Cove. Model comparisons with measurements are not as favorable at the inlet to Nauset Harbor, but are still good. Compared to the relative quiescence of the entrance to Town Cove, currents were more difficult to measure with the ADCP along the Nauset Inlet transect, since this area is considerably more dynamic and therefore presents challenges for the accurate measurement of currents.

The greatest source of error at the inlet ADCP transect results from the extensive shallow tide flats and shoals in the inlet which did not permit the safe passage of the survey boat. Because the ADCP was not able to measure currents in these shallow areas, which have very swift currents and large flow volumes, a portion of the total flow volume in the inlet channels was not measured. Apart from the measurement difficulties at the inlet, the good comparison of ADCP measurements and modeled flow volumes at Town Cove provide a good additional verification (i.e., in addition to the tide constituent analysis) that the model accurately represents the dynamics of the real physical system.

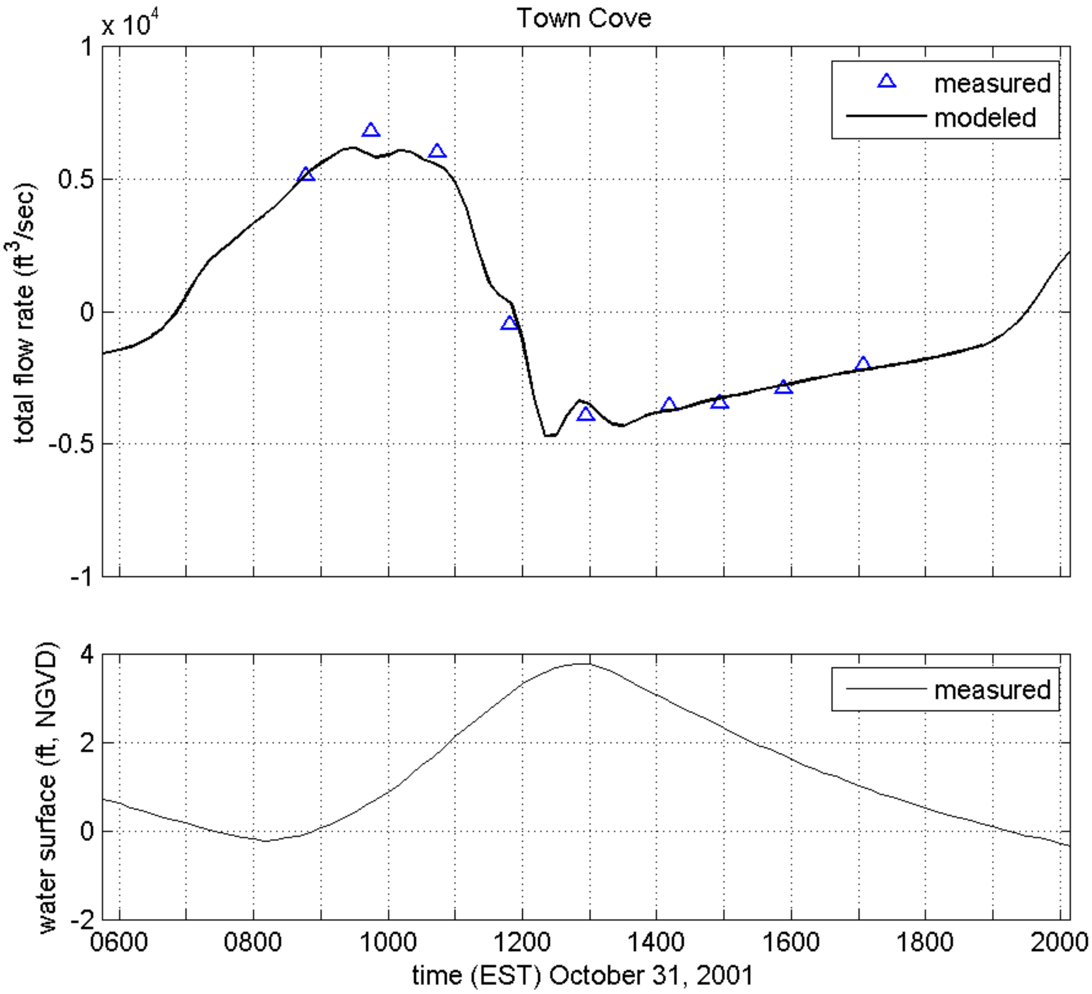


Figure V-20. Comparison of measured volume flow rates versus modeled flow rates (top plot) through the entrance to Town Cove over a tidal cycle on October 31, 2001. Flood flows into the pond are positive (+), and ebb flows out of the pond are negative (-). The bottom plot shows the tide elevation inside Town Cove. R^2 correlation of model and measurements is 0.86 and RMS error is computed to be 1,611 ft^3/sec.

V.4 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through inlet of the Nauset Harbor system, the primary mechanism controlling estuarine water quality within these systems is tidal exchange. For example, a rising tide offshore of Nauset Harbor creates a slope in water surface from the ocean into the upper reaches of the system. Consequently, water flows into (floods) the embayment. Similarly, each estuary drains to the ocean on an ebbing tide. This exchange of water between each system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of each 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 sub-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 Town Cove as an example, the **system residence time** is the average time required for water to migrate from Town Cove, through Nauset Harbor, and out through Nauset Inlet, and alternately where the **local residence time** is the average time required for water to migrate from Town Cove to just Nauset Harbor (not all the way to the inlet). 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. However, for the sub- embayments of Nauset Harbor the **local residence** time is more applicable, since it is assumed that the major portion of the system has relatively good water quality even relative to the coastal ocean receiving waters.

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. 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 can be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The water quality model developed in Section VI provides a valuable tool to evaluate the complex mechanisms governing estuarine water quality.

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 two main 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 mean volume and mean tidal prism of each modeled sub-embayment is presented in Table V-6.

Residence times were averaged for the tidal cycles comprising a representative 7.25 day period (14 tide cycles), and are listed in Table V-7 for the sub-embayment divisions of the Nauset Harbor system. The modeled time period used to compute the flushing rates was the same as the model verification period, and included the transition from neap to spring tide conditions. Model divisions used to define the sub-embayments are shown in Figure V-12. The RMA-2 model calculated flow crossing specified grid lines for each sub-embayment, and this flow data were used to compute the mean tidal prism volume. Since the 7.25-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.

Table V-6. Embayment mean volumes and average tidal prism during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Nauset System	596,433,310	266,532,000
Town Cove	227,949,100	69,940,300
Salt Pond	11,933,800	1,566,100
Mill Pond	39,680,400	11,429,700

Table V-7. Computed System and Local residence times for embayments in the Nauset Harbor system.

Embayment	System Residence Time (days)	Local Residence Time (days)
Nauset System	1.2	1.2
Town Cove	4.4	1.7
Salt Pond	197.1	3.9
Mill Pond	27.0	1.8

The computed flushing rates for Nauset Harbor show that each system generally flushes well, with flushing times of the order of a day. Of all the modeled sub-embayments, Salt Pond has the longest flushing times, with a local flushing time that is nearly 4 days. This deep kettle pond does not flush as well as other sub-embayments due to its large mean volume. Because there is already almost no attenuation of the tide signal from Nauset Bay to inside Salt Pond, it would not be possible to make significant improvements to the flushing characteristics of this sub-embayment by dredging the tidal creek connection the pond to the Nauset system.

Generally, 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 meshes used to model each system, which provided the basis for all the flushing volumes used in the analysis. In addition, limited topographic measurements were available on the extensive marsh plain included in the model

Minor errors may be also 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 offshore Nauset Harbor typically is strong, the “strong littoral drift” assumption is completely appropriate, and would result in only minor errors in residence time calculations. Based on our knowledge of estuarine processes, we estimate that the combined errors due to bathymetric inaccuracies represented in the model grid and the “strong littoral drift” assumption are within 10% to 15% of “true” residence times for the modeled system.

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

Several different types of data and a variety of calculations are required to support the water quality modeling effort for the Nauset Harbor estuary 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 Embayment

Extensive field measurements and hydrodynamic modeling of the embayment were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated model output representing the transport of water within the system. Files of node locations and node connectivity for the RMA-2V model grid were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model was also the computational grid for the water quality model. The period of hydrodynamic output for the water quality model calibration was a 28-tidal cycle period in October 2001. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 29 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 Embayment

Three primary nitrogen loads to the embayment 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 Nauset Harbor estuary system, consisting of the background concentrations of total nitrogen in the waters entering from the Atlantic Ocean. This load is represented as a constant concentration along the seaward boundary of the model grid.

VI.1.3 Measured Nitrogen Concentrations in the Embayment

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 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 is the minimum required to provide a baseline for MEP analysis. Generally, four years of data (collected between 2001 and 2004) were available for stations monitored by SMAST in the Nauset Harbor estuary system, with a few data gaps.

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 Nauset Harbor estuary system. The RMA-4 model is capable of simulating the advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of the Nauset Harbor estuary system. Like the RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other embayments in Southeastern Massachusetts, including systems in Falmouth (Ramsey *et al*., 2000); Mashpee, MA (Howes *et al*., 2004) and Chatham, MA (Howes *et al*., 2003).

Table VI-1. Town of Orleans water quality monitoring data and modeled Nitrogen concentrations for the Nauset Harbor estuary system used in the model calibration plots of Figure VI-2. "Data mean" values are calculated as the average of the separate yearly means. All concentrations are given in mg/L N.

Sub-Embayment	Monitoring station	Mean	s.d. all data	N	model min	model max	model average
Town Cove - Inner	WMO-25	0.600	0.168	36	0.5889	0.6113	0.5976
Town Cove - Inner	WMO-26	0.507	0.116	21	0.5592	0.5986	0.5794
Town Cove - Inner	WMO-27	0.509	0.131	20	0.3694	0.5912	0.5268
Town Cove - Outer	WMO-28	0.416	0.078	15	0.3064	0.5643	0.4434
Town Cove - Outer	WMO-29	0.487	0.120	19	0.3002	0.5452	0.4108
Nauset Marsh - South	WMO-30	0.477	0.156	15	0.274	0.4765	0.3559
Wood Cove	WMO-31	0.510	0.200	13	0.4764	0.5458	0.5076
Nauset Marsh - South	WMO-32	0.422	0.148	33	0.2767	0.4414	0.3305
Mill Pond - Outer	WMO-33	0.512	0.141	16	0.3875	0.4631	0.4293
Mill Pond - Middle	WMO-34	0.503	0.106	21	0.4972	0.5168	0.5067
Mill Pond - Inner	WMO-35	0.611	0.143	21	0.5824	0.6164	0.5993
Nauset Marsh - North	WMO-36	0.481	0.140	20	0.3127	0.4945	0.412
Nauset Marsh - North	WMO-37	0.438	0.079	15	0.2942	0.6229	0.4587
Salt Pond	WMO-38	0.587	0.102	40	0.5735	0.6744	0.6182
Nauset Marsh - North	WMO-39	0.575	0.211	18	0.2832	0.6464	0.4773
Nauset Marsh - North	WMO-40	0.484	0.109	19	0.2771	0.4436	0.3251

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 (based on the USGS watersheds), 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 system.

Figure VI-1. Estuarine water quality monitoring station locations in the Nauset Harbor estuary system. Station labels correspond to those provided in Table VI-1. The approximate location of the threshold station is depicted by the red symbol at station WMO-27.

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 Nauset Harbor estuary 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 the Nauset Harbor estuary system were used for the water quality constituent modeling portion of this study.

Based on measured surface water flow rates from SMAST and groundwater recharge rates from the USGS, the hydrodynamic model was set-up to include the latest estimates of flows from a small stream flowing out of Mary Chase Marsh and into Town Cove. The stream has a mean measured flow rate of 0.9 ft^3/sec (2,150 m^3/day), which is less than 0.1% of the average tidal prism of Nauset Harbor system, indicating this stream has negligible impact on the overall water quality of the estuarine system. The overall groundwater flow rate into the system is 18.4 ft^3/sec (45,100 m^3/day) distributed amongst the watersheds.

For the 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 spin-up period of 29 days. At the end of the spin-up period, the model was run for an additional

28 tidal-cycle (348 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 hydrodynamic inputs for the Nauset Harbor estuary system.

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, 3) summer benthic regeneration, and 4) point source inputs developed from measurements of the freshwater surface flows of the Nauset Harbor Estuarine System. 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 Town Cove were evenly distributed at grid cells that formed the outer edge of the 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 Nauset Harbor estuary 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.3. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment, resulting in a total flux for each sub-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 present conditions, the primary portion of the total loading rate for the system comes from watershed loads.

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 Atlantic Ocean was set at 0.279 mg/L, based on SMAST data from a nearby station in the Atlantic Ocean that is located a little south of the Nauset inlet and closer to Pleasant Bay. The open boundary total nitrogen concentration represents long-term average summer concentrations found at this station.

VI.2.4 Model Calibration

Calibration of the total nitrogen model 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 Figure VI-2. 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 areas of Nauset Harbor 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 systems 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 portion of the estuary.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Nauset Harbor estuary system, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions.**

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Nauset Marsh	10.73	11.25	46.84
Salt Pond	5.01	0.30	19.62
Woods Cove	0.75	0.24	4.66
Mill Pond	4.93	1.07	3.22
Rachel Cove	0.18	0.16	0.00
Town Cove	29.20	5.23	59.74
Nauset Stream	2.39	-	-

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

Embayment Division	E m^2/sec
Nauset Marsh	0.1
Salt Pond	7.0
Town Cove Inner	4.0
Inlet	0.5
Town Cove Outer	15.0
Woods Cove	1.0
Mill Pond Outer	1.0
Mill Pond Inner	0.3
Salt Pond Bay	0.3
Rachel Cove	0.5
Woods Cove	0.7
Town Cove	2.0
Nauset Marsh	2.0
Salt Pond	7.0
Mill Pond	0.3

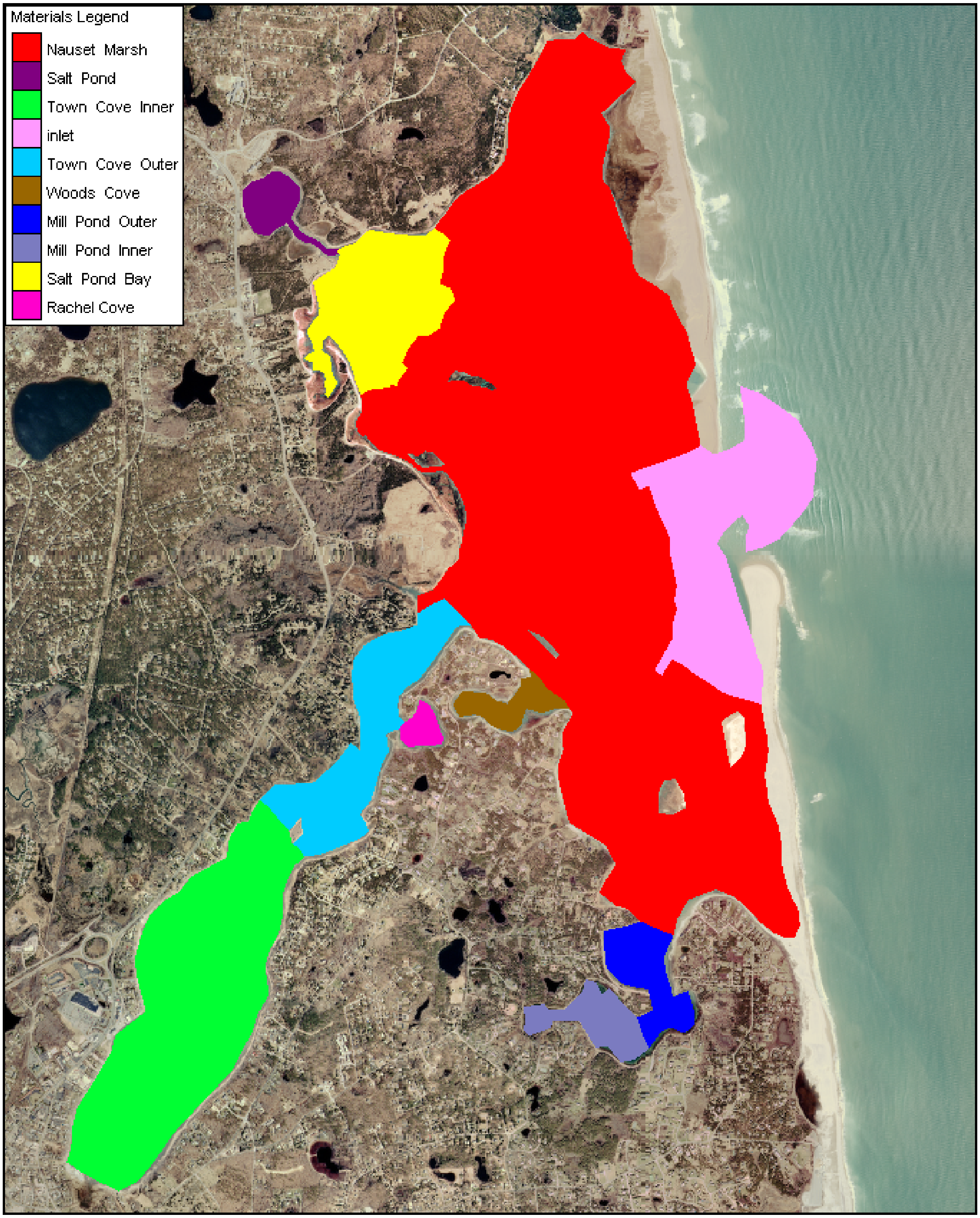


Figure VI-2. Map of the Nauset Harbor system water quality model longitudinal dispersion coefficients. Color patterns designate the different areas used to vary model dispersion coefficient values.

Comparisons between model output and measured nitrogen concentrations are shown in plots presented in Figure VI-3. In these plots, means of the water column data and a range of one standard deviation 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.

Also presented in this figure are unity plot comparisons of measured data verse modeled target values for the system. The model fit is excellent for the Nauset Harbor system, with rms error of 0.05 mg/L and an R^2 correlation coefficient of 0.84.

A contour plot of calibrated model output is shown in Figure VI-4 for the Nauset Harbor estuary system. In the figure, color contours indicate nitrogen concentrations throughout the model domain. The output in the figure show average total nitrogen concentrations, computed using the full 14-tidal-day model simulation output period.

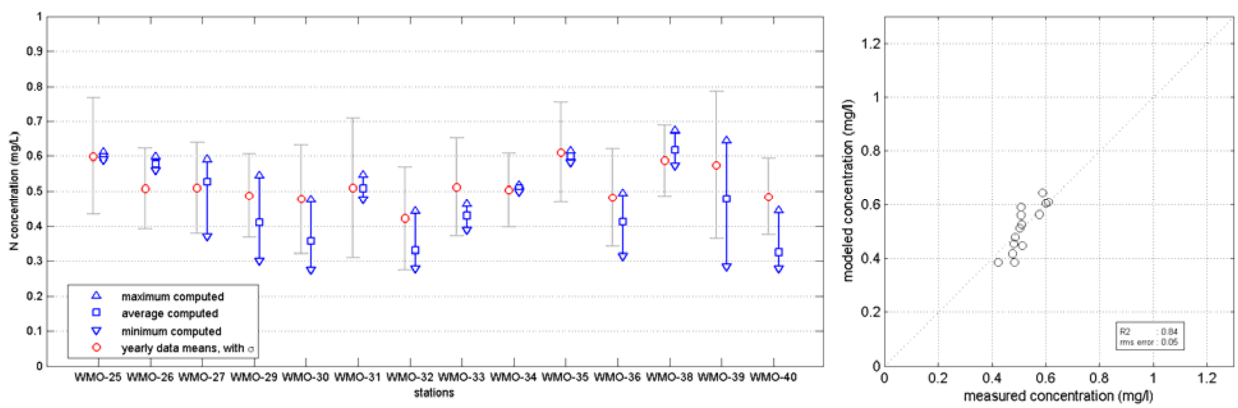


Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Nauset Harbor estuary system. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed 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. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

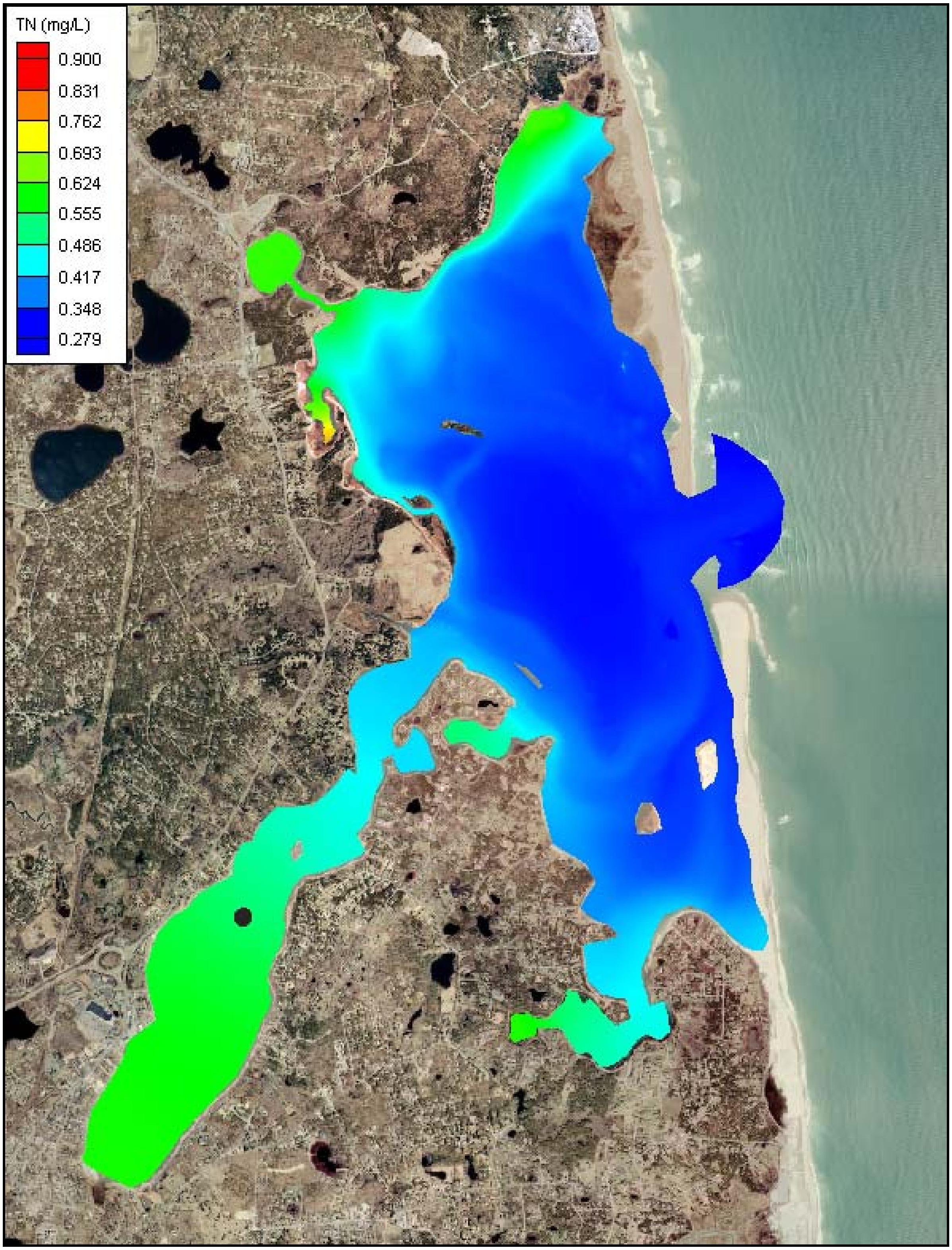


Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario for the Nauset Harbor estuary system. The approximate locations of the sentinel threshold station for Nauset Harbor estuary system is shown by the black symbol (WMO-27 in Town Cove).

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 Nauset Harbor estuary system using salinity data collected at the same stations as the nitrogen data. The data inputs required for the RMA-4 salinity model of the system was salinity at all the water quality monitoring stations, in addition to the RMA-2 hydrodynamic model output, salinity at the model open boundary, groundwater inputs, and surface water streams. The open boundary salinity was set at 31.28 ppt. For groundwater and surface water inputs, salinities were set at 0 ppt. Total freshwater input used for the model was 18.4 ft^3/sec (45,100 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed evenly in each sub-embayment through the use of several "rainwater" element input points positioned along each model's land boundary.

Comparisons of modeled and measured salinities are presented in Figure VI-5, with contour plots of model output shown in Figure VI-6. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in the Nauset Harbor estuary system. The rms error of the models was 1.07 ppt, and the correlation was 0.77. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical system.

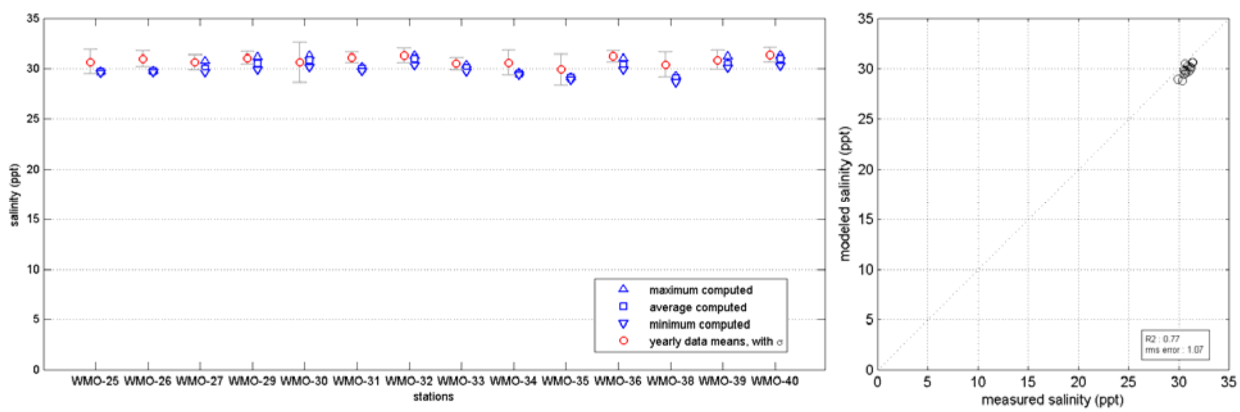


Figure VI-5. Comparison of measured and calibrated model output at stations in the Nauset Harbor estuary system. For the left plots, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation 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. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

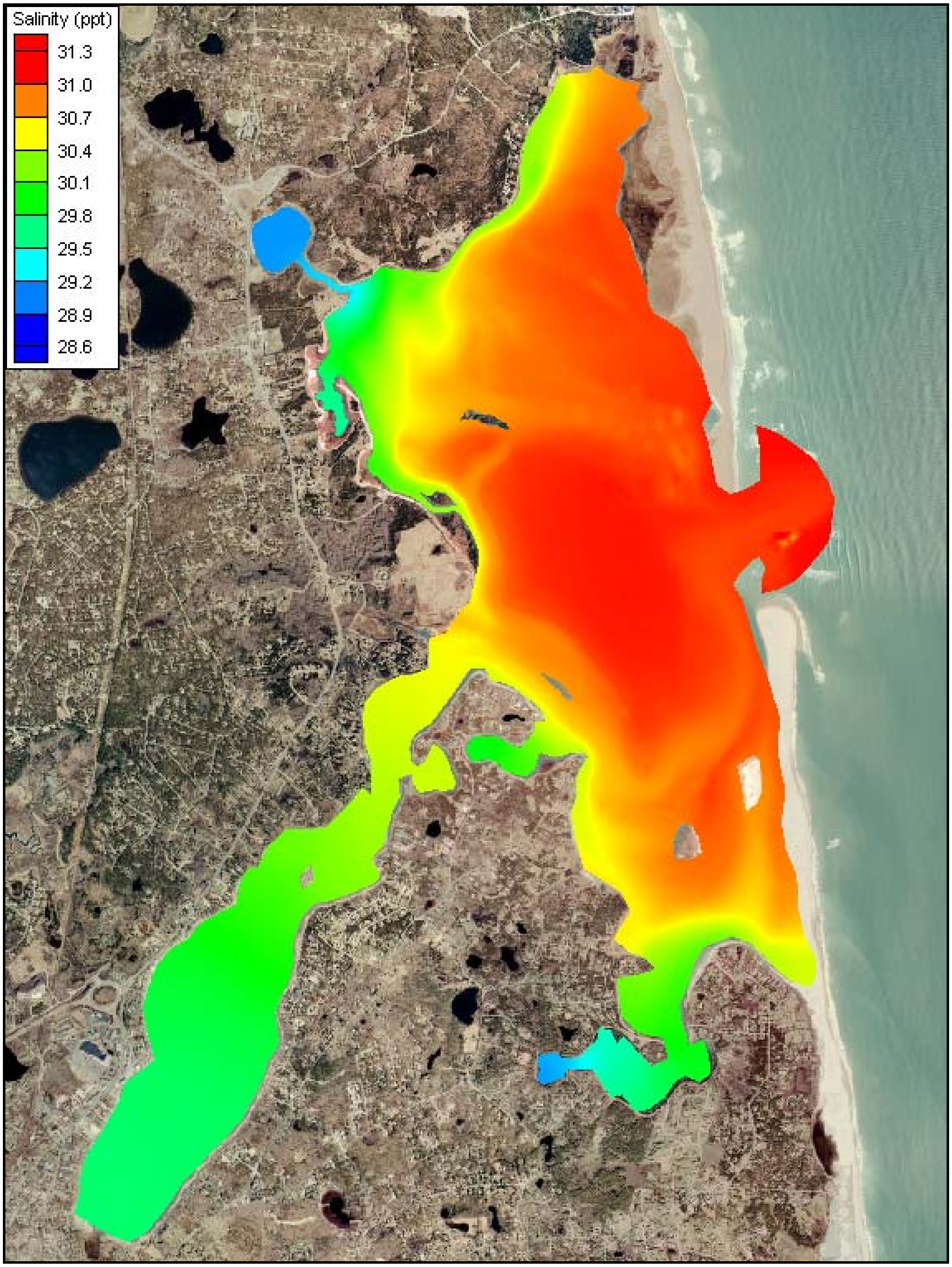


Figure VI-6. Contour plot of modeled salinity (ppt) in the Nauset Harbor estuary system.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the embayment system, two standard water quality modeling scenarios were run: a "build-out" scenario 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-embayments, as well as a natural forest within the Nauset watershed. Comparisons of the alternate watershed loading analyses are shown in Table VI-4. Loads are presented in kilograms per day (kg/day) in this Section, since it is inappropriate to show benthic flux loads in kilograms per year due to seasonal variability.

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Nauset Harbor estuary 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 (kg/day)	build out % change	no load (kg/day)	no load % change
Nauset Marsh	10.73	12.39	15.5%	1.02	-90.5%
Salt Pond	5.01	5.30	5.8%	0.29	-94.2%
Woods Cove	0.75	0.84	12.0%	0.04	-94.7%
Mill Pond	4.93	5.90	19.7%	0.18	-96.3%
Rachel Cove	0.18	0.19	5.6%	0.01	-94.4%
Town Cove	29.20	32.25	10.4%	0.88	-97.0%
Nauset Stream	2.39	2.65	10.9%	0.08	-96.7%

VI.2.6.1 Build-Out

In general, under the build-out modeling scenario, certain sub-embayments would be impacted more than others. For example, the build-out scenario indicates that there would be more than a 19% increase in watershed nitrogen load to Mill Pond as a result of potential future development, but only an increase of 5.8% for Salt Pond. For the no load scenario, a majority of the load entering the watershed is removed; therefore, the load is lower than existing conditions by over 96% for Mill Pond and 94% for the Salt Pond.

For the build-out scenario, a breakdown of the total nitrogen load entering the Nauset Harbor estuary system sub-embayments is shown in Table VI-5. The benthic flux for the build-out scenarios is assumed to vary proportional to the watershed load, where an increase in watershed load will result in an increase in benthic flux (i.e., a positive change in the absolute value of the flux), and *vice 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 sub-embayment and surface water loads used for total nitrogen modeling of the Nauset Harbor estuary 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)
Nauset Marsh	12.39	11.25	49.34
Salt Pond	5.30	0.30	20.67
Woods Cove	0.84	0.24	4.78
Mill Pond	5.90	1.07	3.50
Rachel Cove	0.19	0.16	0.00
Town Cove	32.25	5.23	63.04
Nauset Stream	2.65	-	-

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of the Nauset Harbor estuary system was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., the Atlantic Ocean) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most at the Inner Mill Pond station (10.4%), while the change was less noticeable in Nauset Marsh (5.7%). Color contours of model output for the build-out scenario are present in Figure VI-7. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-4, which allows direct comparison of nitrogen concentrations between loading scenarios. For typical systems, a total nitrogen concentration greater than 0.5 mg/L leads to negative impacts in benthic fauna.

Table VI-6. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Nauset Harbor estuary system. The sentinel threshold stations are in bold print.				
Sub-Embayment	Monitoring station	present (mg/L)	build-out (mg/L)	% change
Town Cove - Inner	WMO-25	0.5976	0.6167	6.0%
Town Cove - Inner	WMO-26	0.5794	0.5975	6.0%
Town Cove - Inner	**WMO-27**	**0.5268**	**0.5418**	**6.1%**
Town Cove - Outer	WMO-28	0.4434	0.4534	6.1%
Town Cove - Outer	WMO-29	0.4108	0.4188	6.1%
Nauset Marsh - South	WMO-30	0.3559	0.3606	6.1%
Wood Cove	WMO-31	0.5076	0.5206	5.7%
Nauset Marsh - South	WMO-32	0.3305	0.3337	6.2%
Mill Pond - Outer	WMO-33	0.4293	0.4422	8.6%
Mill Pond - Middle	WMO-34	0.5067	0.5284	9.5%
Mill Pond - Inner	WMO-35	0.5993	0.6325	10.4%
Nauset Marsh - North	WMO-36	0.412	0.4196	5.7%
Nauset Marsh - North	WMO-37	0.4587	0.4692	5.8%
Salt Pond	WMO-38	0.6182	0.6381	5.9%
Nauset Marsh - North	WMO-39	0.4773	0.4904	6.6%
Nauset Marsh - North	WMO-40	0.3251	0.3279	6.1%

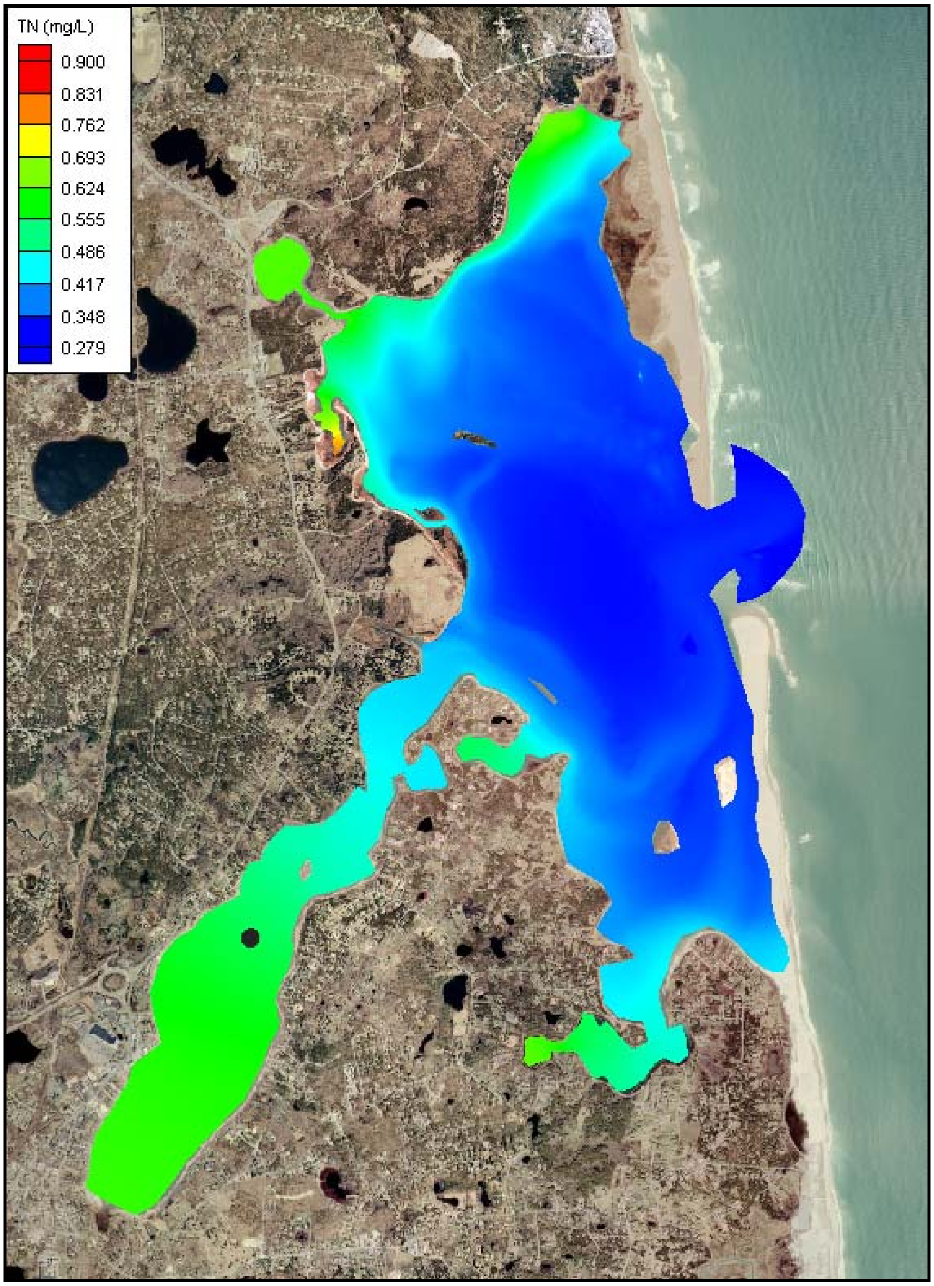


Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in the Nauset Harbor estuary system under projected build-out loading conditions. The approximate location of the sentinel threshold station for the Nauset Harbor estuary system is shown by the black symbol (WMO-27 in Town Cove).

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") scenario is shown in Table VI-7. The benthic flux input to each embayment was reduced (toward zero) based on the reduction in the watershed load (as discussed in Section VI.2.6.1). Compared to the modeled present conditions and build-out scenario, atmospheric deposition directly to each sub-embayment becomes a greater percentage of the total nitrogen load as the watershed load and related benthic flux decrease.

Table VI-7. "No anthropogenic loading" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of Nauset Harbor estuary 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)
Nauset Marsh	1.02	11.25	35.27
Salt Pond	0.29	0.30	13.45
Woods Cove	0.04	0.24	3.45
Mill Pond	0.18	1.07	1.35
Rachel Cove	0.01	0.16	0.00
Town Cove	0.88	5.23	31.29
Nauset Stream	0.08	-	-

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Again, total nitrogen concentrations in the receiving waters (i.e., the Atlantic Ocean) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was significant as shown in Table VI-8, with reductions of 39% to almost 59%. Results for the system are shown pictorially in Figure VI-8.

Table VI-8. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the Nauset Harbor estuary system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The sentinel threshold stations are in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Town Cove - Inner	WMO-25	0.5976	0.4369	-50.4%
Town Cove - Inner	WMO-26	0.5794	0.4276	-50.5%
Town Cove - Inner	**WMO-27**	**0.5268**	**0.4015**	**-50.6%**
Town Cove - Outer	WMO-28	0.4434	0.3605	-50.4%
Town Cove - Outer	WMO-29	0.4108	0.3444	-50.4%
Nauset Marsh - South	WMO-30	0.3559	0.3178	-49.5%
Wood Cove	WMO-31	0.5076	0.3988	-47.6%
Nauset Marsh - South	WMO-32	0.3305	0.3057	-48.2%
Mill Pond - Outer	WMO-33	0.4293	0.3501	-52.7%
Mill Pond - Middle	WMO-34	0.5067	0.3816	-54.9%
Mill Pond - Inner	WMO-35	0.5993	0.4122	-58.4%
Nauset Marsh - North	WMO-36	0.412	0.3551	-42.8%
Nauset Marsh - North	WMO-37	0.4587	0.3796	-44.0%
Salt Pond	WMO-38	0.6182	0.4353	-53.9%
Nauset Marsh - North	WMO-39	0.4773	0.3983	-39.8%
Nauset Marsh - North	WMO-40	0.3251	0.3057	-42.1%

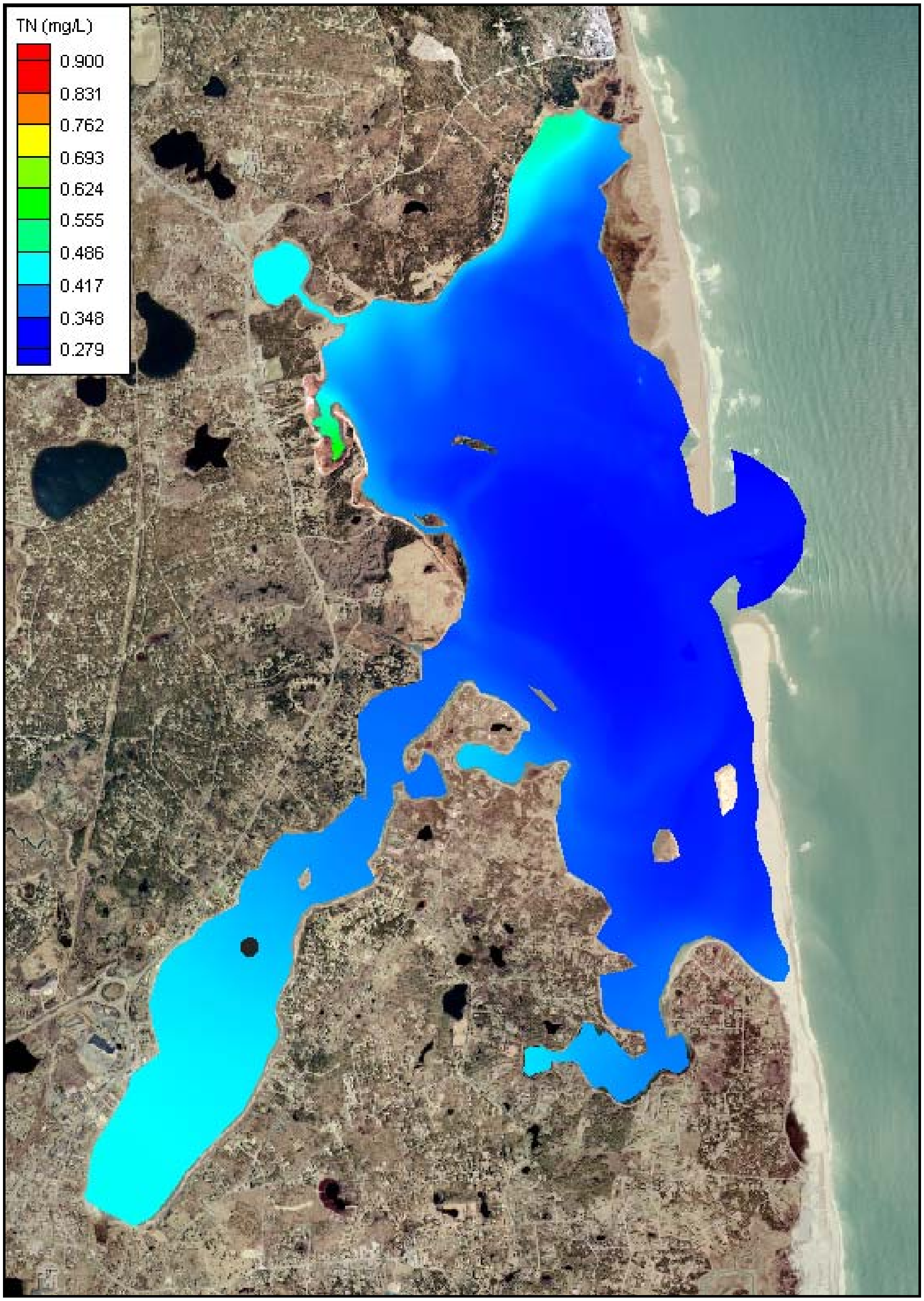


Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in the Nauset Harbor estuary system under no anthropogenic loading conditions. The approximate location of the sentinel threshold station for the Nauset Harbor estuary system is shown by the black symbol (WMO-27 in Town Cove).

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 Nauset Estuary our assessment is based upon data from the water quality monitoring database (2001-2009) and surveys of eelgrass distribution (1951 and 2001), benthic animal communities, eelgrass point surveys, and sediment characteristics, and dissolved oxygen records conducted during the summer and fall of 2003. 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). It should be noted that nitrogen enrichment occurs through 2 primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or less than optimal rates of flushing due to restriction of tidal exchange with the low nitrogen waters of the Atlantic Ocean. The Nauset Estuary has increasing nitrogen loading from its watershed from shifting land-uses. Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs, so that maximizing tidal exchange and circulation within the estuary should be a part of any planning for managing nitrogen enrichment.

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 at strategic locations throughout the Nauset Estuary 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 loss in Cape Cod estuaries associated with nitrogen enrichment is generally through decreased light penetration resulting from increased phytoplankton biomass and resulting suspended organic particles, as well as shading by epiphytes (small plants that colonize eelgrass shoots) and sometimes by drift macroalgae. Each of these factors is a result of nitrogen enrichment and all result in stress to eelgrass beds. 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 Nauset 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. Analysis of inorganic N/P molar ratios within the watercolumn of the Nauset Estuary support this contention that nitrogen is the nutrient to be managed, as the ratio ranges from 6.9 to 3.9 among the component tidal basins, far below the Redfield Ratio value (16) indicating that nitrogen additions will increase phytoplankton production, organic matter levels and turbidity within this system. Increased phytoplankton and organic matter levels increase oxygen consumption within the waters and sediments and increase the extent of oxygen depletion and habitat impairment. Within the Nauset Estuary, temporal changes in eelgrass distribution provided a strong basis for evaluating recent increases in nutrient enrichment.

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

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, USEPA[2] suggests that the chronic protective oxygen level to support growth of estuarine animals is 4.8 mg L^{-1}, with a limit for survival of juvenile and adult organisms of 2.3 mg L^{-1}. However, studies have demonstrated that slightly higher oxygen levels, 3.0 mg/L, can still be lethal to larval fish and crustaceans (Poucher and Coiro 1997). Massachusetts State Water Quality Classification indicates that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Nauset Estuarine 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 (e.g. Popponesset Bay, 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.

[2] USEPA 2000. Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras (133 p.).

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) and can lead to erroneous conclusions regarding the overall health/impairment of a system. 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 basins comprising the Nauset Estuary (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 were collected within the Nauset Estuary during the summer of 2003.

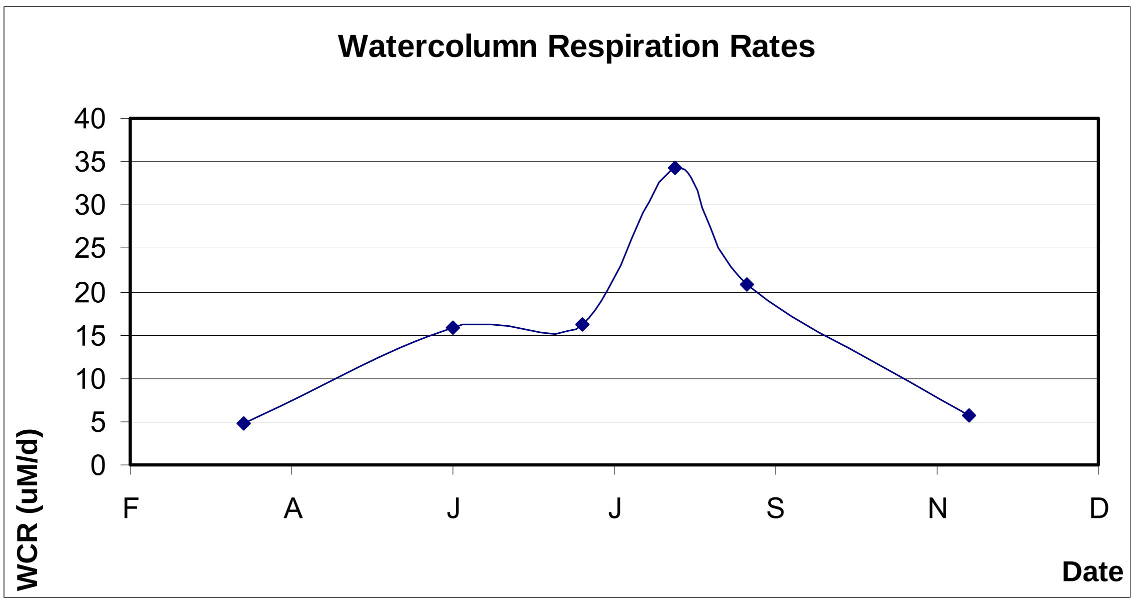


Figure VII-1. Average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Nauset Estuary 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. The high degree of temporal variation in bottom water dissolved oxygen concentration at each mooring site, underscores the need for continuous monitoring within these systems.

Figure VII-2. Aerial Photograph of the Nauset Harbor system in the Town of Orleans showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2003.

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 29-32 day deployment period (depending on the mooring) that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion events 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 and chlorophyll-*a* levels indicate highly nutrient enriched waters and impaired habitat quality at all mooring sites within each estuary (Figures VII-3 through VII-9). The oxygen data are consistent with high organic matter loads from phytoplankton production (chlorophyll-*a* levels) indicative of nitrogen enrichment of these estuarine systems (Figures VII-4, 7 and 9).

The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in various locations throughout a given system. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration indicates that the sub-embayments to the Nauset Estuarine System (particularly Salt Pond, Town Cove and Wood Cove) are nitrogen and organic matter enriched.

The embayment specific results are as follows:

***Salt Pond* (Figures VII-3 and VII-4):**

The Salt Pond instrument mooring was located at the far end of the Nauset system in a drowned kettle pond tributary to the salt marsh basin of Salt Pond Bay ~ 3.0 km from Nauset Inlet. The Salt Pond Basin is >6 meters in depth (Figure V-13) and has historically shown periodic hypoxic/anoxic conditions in bottom water. The mooring was generally located slightly off-center of the Salt Pond basin at 3 m depth to capture the mid basin depth sediments and avoid the deep "hole". Since the deep basin waters are periodically anoxic, the mooring was placed to give a more representative measure of most of the benthic habitat within the basin. As a result the readings do not represent the minimum oxygen conditions. The 2003 summer sediment survey confirmed anoxia and sulfidic conditions in the deep water of Salt Pond. Moderate daily excursions in oxygen levels were observed at this location, ranging from approximately air equilibration (7-8 mg L^{-1}) to hypoxic conditions, with levels frequently declining to less than 4 mg L^{-1} and periodically to <3 mg L^{-1} (Figure VII-3, Table VII-1). A temporal decline in oxygen levels was observed from ~7 mg L^{-1} at the beginning of the deployment period to significant periods of oxygen <4 mg L^{-1} for the latter part of the deployment period.

Oxygen levels regularly persisted between 4-7 mg L^{-1}, but occasionally levels exceeded 8 mg L^{-1}. Over the 32 day deployment there does appear to be an obvious phytoplankton bloom at the beginning of the deployment period where chlorophyll-a increased to a significant level, between 15 and 30 ug L^{-1}. During the latter part of the deployment, chlorophyll-a levels declined as the bloom senesced to 1-3 ug L^{-1}, with an apparent second bloom beginning in the last week of deployment as seen by chlorophyll-a levels rising to ~10 ug L^{-1}. The average chlorophyll-a over the deployment period was 6.8 ug L^{-1}, with a range of 1-30 ug l^{-1}. Chlorophyll-*a* levels exceeded the 10 ug L^{-1} benchmark ~20% of the time (Table VII-2, Figure VII-4). In ecological terms, average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments. Phytoplankton levels within Salt Pond may be associated with the overall Nauset Estuary as a similar temporal pattern was observed in Town Cove during this period. Oxygen and chlorophyll levels are indicative of significantly impaired and moderately impaired conditions, respectively in this portion of the Nauset system and consistent with nitrogen enrichment.

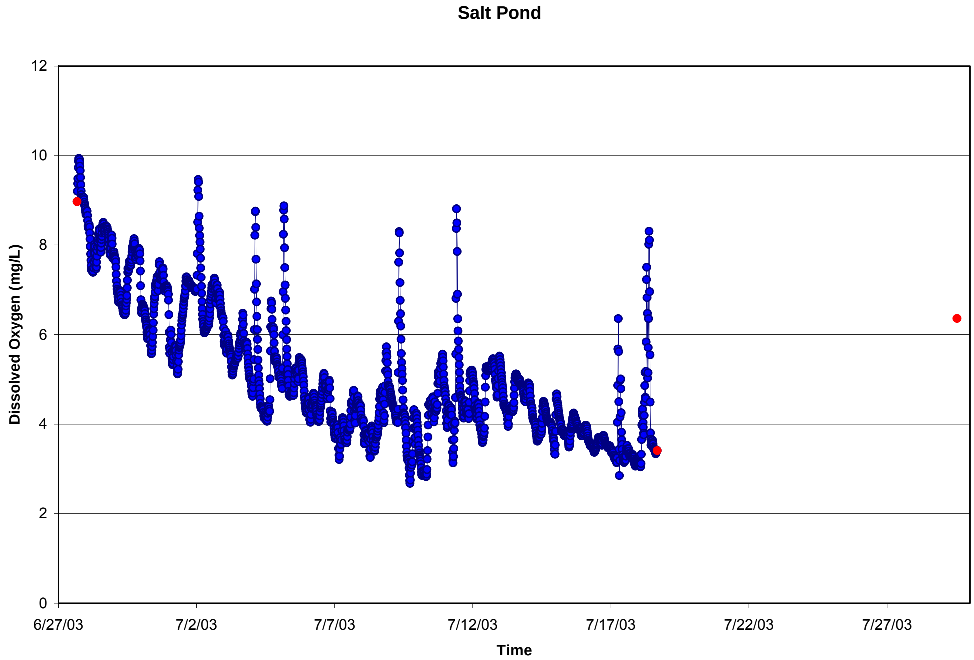


Figure VII-3. Bottom water record of dissolved oxygen at Salt Pond station, Summer 2003. Calibration samples represented as red dots. DO sensor failed during the last week.

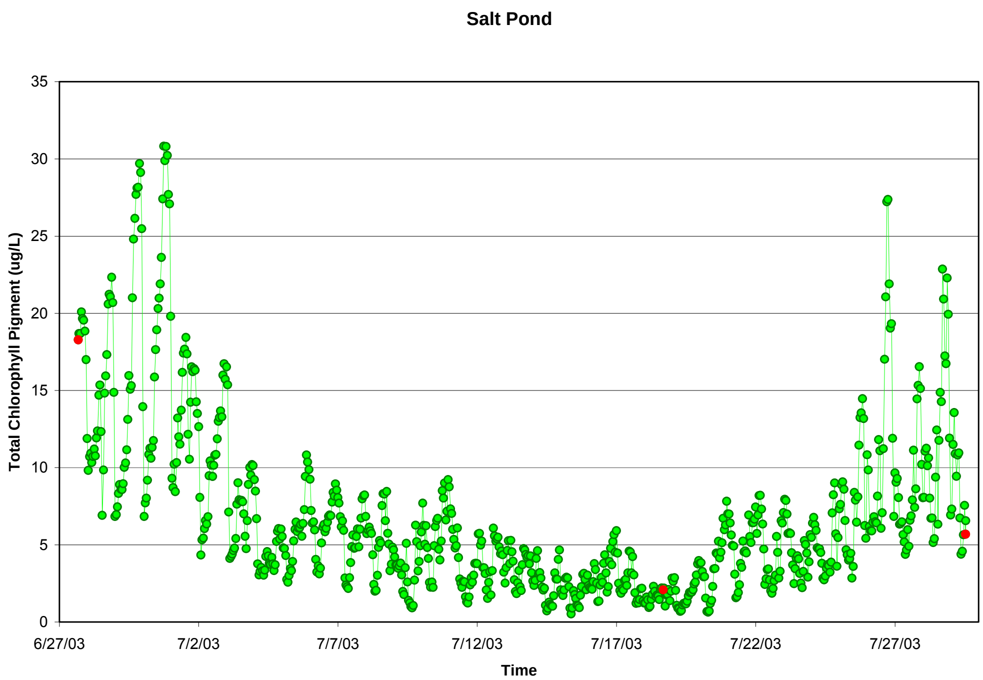


Figure VII-4. Bottom water record of Chlorophyll-*a* in Salt Pond mid depth station, Summer 2003. Calibration samples represented as red dots.

Wood Cove **(Figure VII-5):**

The Wood Cove instrument mooring was located in a small tributary basin situated off one of the main tidal channels connecting the Nauset Inlet to Town Cove. The shallow basin of Wood Cove is located immediately south of Stony Island and is ~ 3 km from the inlet. Large daily excursions in oxygen levels were observed at this location, ranging from levels well above (10-12 mg L^{-1}) air equilibration (7-8 mg L^{-1}) to hypoxic conditions where levels frequently decline to 3 mg L^{-1} and even approach 1 mg L^{-1} (Figure VII-5, Table VII-1). Additionally, levels frequently exceeded 10 mg L^{-1} during the deployment period. Oxygen was <4 mg L^{-1} for 7% of the record.

At this mooring location the chlorophyll sonde failed and it was not possible to obtain a record of chlorophyll levels for comparison to the oxygen record. Chlorophyll-*a* measured by the Orleans Water Quality Monitoring Program was generally low, averaging ~4 ug L^{-1}. However, benthic surveys of Wood Cove indicated a moderate accumulation of filamentous macroalgae. This indicates that the oxygen levels in excess of air equilibration were likely driven primarily by macroalgae rather than phytoplankton (as was the case for Salt Pond). This is also consistent with the relatively shallow depth of the basin (<1 meter). Both the macroalgal accumulations and the oxygen record are consistent with stress to benthic communities and the absence of eelgrass from this basin.

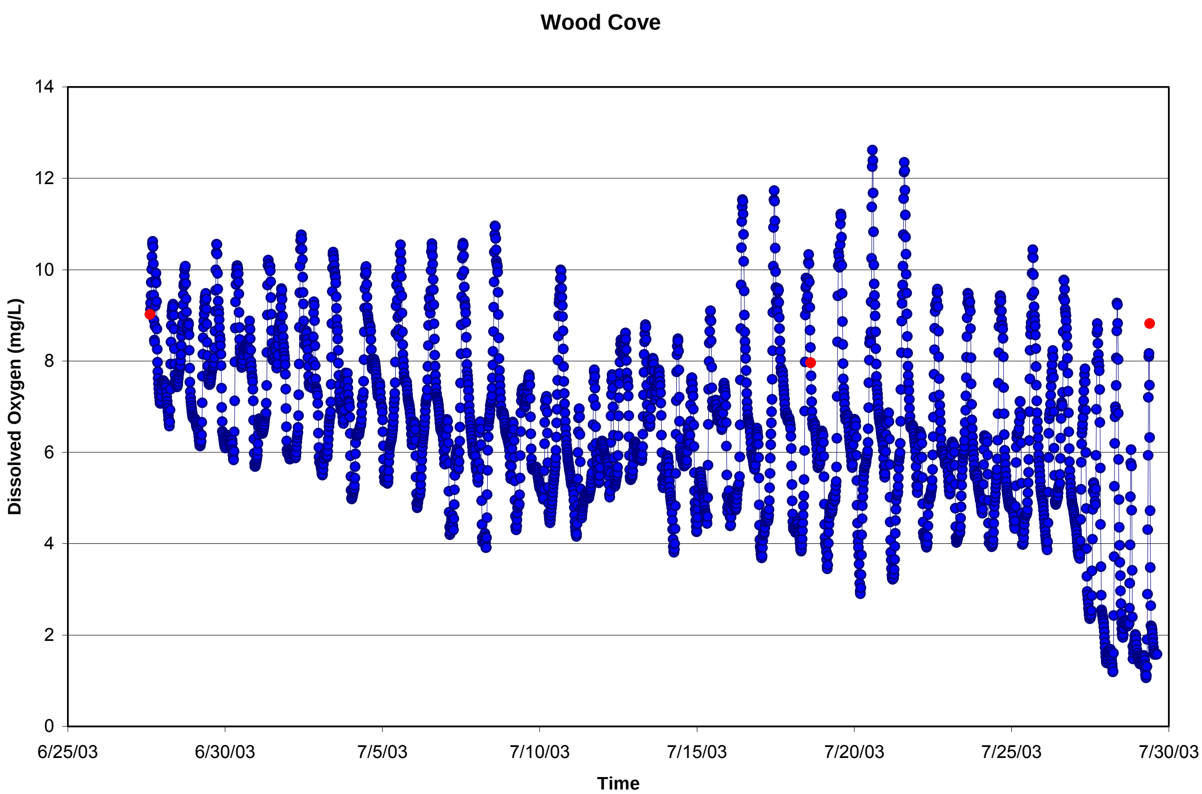


Figure VII-5. Bottom water record of dissolved oxygen in Wood Cove station, Summer 2003. Calibration samples represented as red dots.

Town Cove **(Figures VII-6 and VII-7):**

The Town Cove instrument mooring was located at the upper tidal reach (southern end) of the cove approximately 1.75 km from Hopkins Island and ~ 7 km from Nauset Inlet. The Town Cove mooring was centrally located in the deeper basin in the upper third of Town Cove (Figure VII-2). Large daily excursions (2-6 mg L^{-1}) in oxygen levels were observed at this location, ranging from levels at and above air equilibration (7-10 mg L^{-1}) to hypoxic/anoxic conditions. Oxygen levels were frequently less than 2 mg L^{-1} and periodically approach 0 mg L^{-1} (Figure VII-6, Table VII-1). Oxygen levels < 3 mg L^{-1} were measured for 38 percent of the deployment period.

Oxygen levels rarely exceeded 8 mg L^{-1} and most of the daily excursion appeared to be related to ventilation of the bottom water, rather than photosynthesis. This is consistent with the low levels of macroalgae and, during the middle part of the record, chlorophyll-*a*. Over the 29 day deployment there does appear to be a large phytoplankton bloom at the beginning of the deployment period where chlorophyll-a increase to a significant level, 20-30 ug L^{-1}. During the middle portion of the deployment, the bloom had dissipated and chlorophyll-a levels declined to 1-5 ug L^{-1}. The final portion of the deployment saw the beginning of a second bloom with chlorophyll-*a* gain increasing to between 5 and 15 ug L^{-1}. It appears that the oxygen depletion was inversely correlated with phytoplankton biomass (chlorophyll-*a*) over the period of record. It should be noted that the dual bloom pattern in Town Cove paralleled the chlorophyll record collected simultaneously in Salt Pond.

Both oxygen and chlorophyll levels are consistent with impairment to eelgrass and benthic animal communities in southeastern Massachusetts estuaries. Oxygen frequently declined to <1 mg L^{-1} and chlorophyll averaged 8.5 ug L^{-1}, exceeding the 10 ug L^{-1} benchmark ~28% of the time (Table VII-2, Figure VII-7). In ecological terms, average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

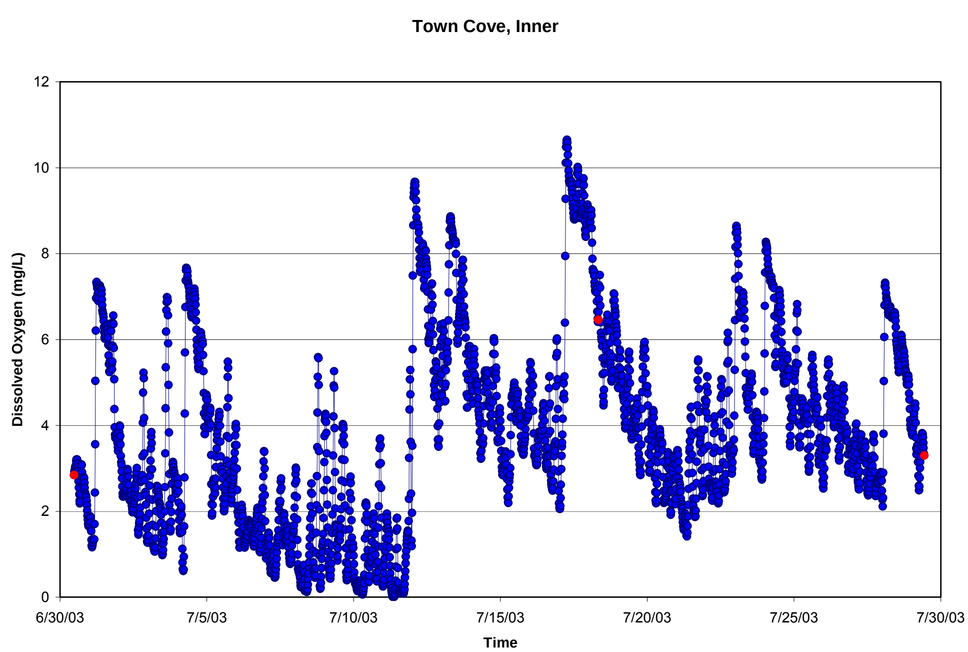


Figure VII-6. Bottom water record of dissolved oxygen at Town Cove, Inner station, Summer 2003. Calibration samples represented as red dots.

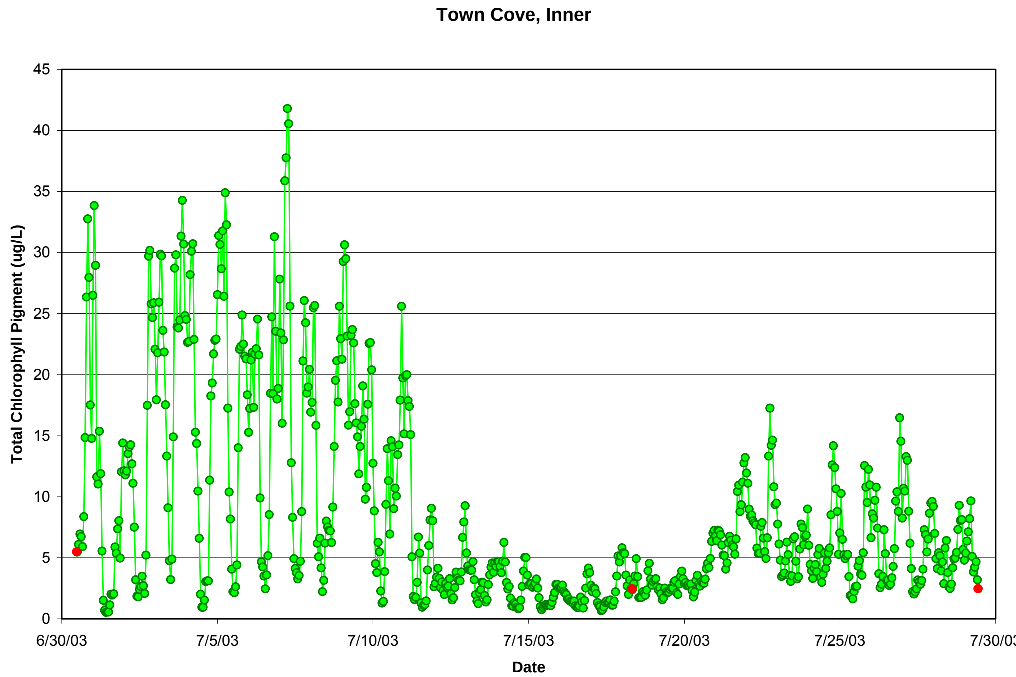


Figure VII-7. Bottom water record of Chlorophyll-*a* in Town Cove station, Summer 2003. Calibration samples represented as red dots. The dual bloom was also observed in the Salt Pond record.

Mill Pond **(Figures VII-8 and VII-9):**

The Mill Pond basin is located at the southern end of the Nauset Estuary. The Pond is a tributary terminal basin situated off one of the main tidal channels of Nauset Marsh. The mooring in Mill Pond was located approximately 4.5 km from Nauset Inlet. The Mill Pond mooring was centrally located in the main basin of Mill Pond, not the small inner basin or the more open reach between the mid basin and Nauset Marsh. The inner basin has dense accumulations of macroalgae compared to the mid and outer basins. The Mill Pond mooring, like the Salt Pond mooring was situated at 3.7 m depth to capture the mid basin depth sediments and avoid the deep "hole" (>8 meters). Since the deep basin waters are periodically anoxic, the mooring was placed to give a more representative measure of most of the benthic habitat within the basin. As a result the readings do not represent the minimum oxygen conditions. The 2003 summer sediment survey confirmed anoxia and sulfidic conditions in the deep water of Mill Pond.

The waters overlying the shallow sediments (<3.7 m) in Mill Pond showed small daily excursions in oxygen levels compared to the oxygen data collected at the other moorings within the Nauset Estuary (see above). Oxygen levels generally ranged from near air equilibration (7-8 mg L^{-1}) to slightly lower conditions where levels occasionally decline to 5 mg L^{-1} (Figure VII-8, Table VII-1). Oxygen levels < 5 mg L^{-1} were measured only for 1 percent of the deployment period.

Oxygen levels regularly persisted between 6-8 mg L^{-1} but only exceeded 8 mg L^{-1}.at the beginning of the deployment coincident to a phytoplankton bloom, as well as for a brief period in the middle of the deployment, which corresponded with a second bloom. Over the 32 day deployment multiple phytoplankton blooms were observed at 10-14 day intervals. The first was on-going at the time of deployment with chlorophyll levels of between 15 and 30 ug L^{-1}. The second bloom was near the middle portion of the deployment, where chlorophyll-a levels were generally between 10 and 30 ug L^{-1}. After the decline of the second bloom a third smaller bloom was observed with chlorophyll-a levels between 5 and 20 ug L^{-1}. Oxygen and chlorophyll levels are indicative of moderate to significantly impaired conditions in Mill Pond in this portion of the Nauset system. The system is nitrogen enriched with average chlorophyll-*a* levels of 10.8 ug L^{-1} and chlorophyll-*a* levels exceeding the 10 ug L^{-1} benchmark ~49% of the time (Table VII-2, Figure VII-9). In ecological terms, average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

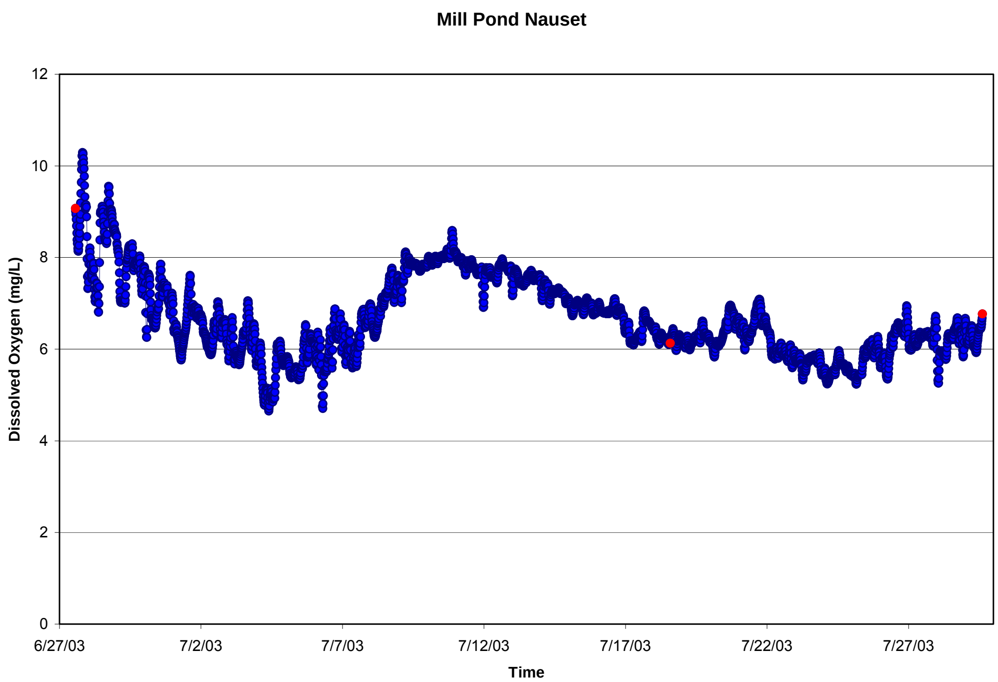


Figure VII-8. Bottom water record of dissolved oxygen in Mill Pond station, Summer 2003. Calibration samples represented as red dots.

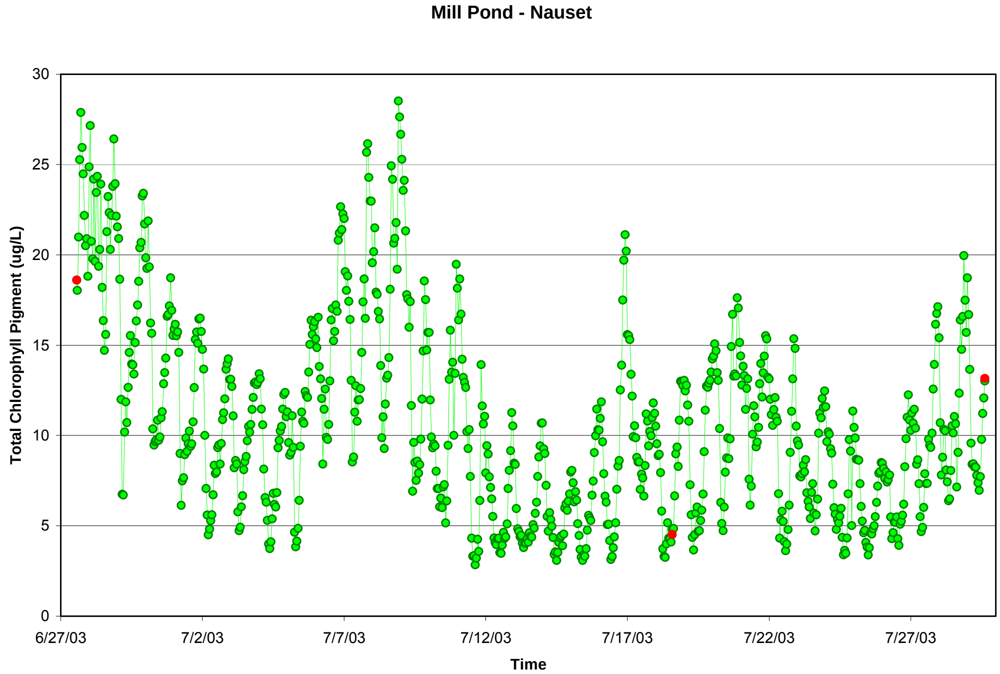


Figure VII-9. Bottom water record of Chlorophyll-*a* in Mill Pond station, Summer 2003. Calibration samples represented as red dots.

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

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Wood Cove	**6/27/2003**	**7/29/2003**	32.0	13.04	6.29	2.23	1.36
			Mean	0.23	0.17	0.14	0.27
			Min	0.02	0.01	0.02	0.02
			Max	0.54	0.52	0.50	0.49
			S.D.	0.14	0.12	0.15	0.19
Salt Pond	**6/27/2003**	**7/29/2003**	31.9	18.31	14.07	6.76	0.76
			Mean	0.38	0.29	0.16	0.05
			Min	0.01	0.01	0.01	0.01
			Max	5.79	3.56	1.46	0.21
			S.D.	1.03	0.61	0.27	0.05
Town Cove	**6/30/2003**	**7/29/2003**	29.0	22.99	20.09	16.07	11.09
			Mean	0.92	0.46	0.32	0.22
			Min	0.01	0.01	0.01	0.01
			Max	7.20	3.04	2.77	1.18
			S.D.	1.63	0.67	0.52	0.28
Mill Pond	**6/27/2003**	**7/29/2003**	32.1	7.43	0.33	0.00	0.00
			Mean	0.20	0.08	N/A	N/A
			Min	0.01	0.05	0.00	0.00
			Max	2.69	0.10	0.00	0.00
			S.D.	0.45	0.02	N/A	N/A

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

Mooring Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Wood Cove	6/27/2003	7/29/2003	32.0					
Meter Malfunction			Mean					
			Min					
			Max					
			S.D.					
Salt Pond	6/27/2003	7/29/2003	32.0	16.58	6.21	3.00	1.38	0.67
Mean Chl Value = 6.81 ug/L			Mean	0.43	0.26	0.25	0.20	0.22
			Min	0.04	0.04	0.04	0.04	0.08
			Max	4.33	0.83	0.63	0.46	0.29
			S.D.	0.77	0.26	0.17	0.16	0.12
Town Cove	6/30/2003	7/29/2003	29.0	14.83	8.17	5.50	3.75	1.83
Mean Chl Value = 8.55 ug/L			Mean	0.39	0.34	0.37	0.17	0.11
			Min	0.04	0.04	0.04	0.04	0.04
			Max	1.63	1.00	0.71	0.67	0.33
			S.D.	0.37	0.30	0.27	0.15	0.08
Mill Pond	6/27/2003	7/29/2003	32.1	27.50	15.63	6.71	2.50	0.46
Mean Chl Value = 10.8 ug/L			Mean	0.98	0.36	0.27	0.18	0.09
			Min	0.04	0.04	0.04	0.04	0.04
			Max	6.08	1.54	0.92	0.46	0.17
			S.D.	1.36	0.34	0.27	0.12	0.05

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

An eelgrass survey and analysis of historical data was conducted for the Nauset Harbor System by the MassDEP Eelgrass Mapping Program (C. Costello). The most recent survey was conducted in 2001, supplemented by system-wide diver survey in 2003 by conducted by MEP staff. Additional analysis of available aerial photographs 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 2001 map was field validated. The MEP Technical Team also conducted a search of available technical documents for possible observations of eelgrass health or coverage within this system. The primary use of the 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 2001 (Figure VII-10); the period in which watershed nitrogen loading significantly increased to its present level. This temporal information was used to determine the stability of the eelgrass community.

At present, eelgrass has nearly disappeared from the Nauset Estuary, with only a small area remaining adjacent Nauset Inlet. The observed loss is consistent with the level of nitrogen enrichment and tidal flows within this system and clearly indicates impairment of this resource. The overall pattern of eelgrass distribution and temporal decline in coverage is fully consistent with the spatial pattern of nitrogen enrichment (Section VI) and oxygen and chlorophyll levels in the various basins (see above). The pattern of decline is typical of environmental changes wrought by nutrient enrichment. Nutrient enrichment tends to result in loss of eelgrass habitat in the more tidally restricted basins, e.g. Town Cove, which also tend to be the focus areas for watershed nitrogen inputs. Loss is first in the deeper waters (like in kettle basins) where increases in turbidity from increased phytoplankton production cause shading of the bottom.

The pattern of loss from the tidal reaches furthest from the inlet can also be seen in the Nauset System, where the remaining eelgrass is adjacent the main inlet.

Figure VII-10. Eelgrass bed distribution within the Nauset Harbor System. Beds delineated by MassDEP Eelgrass Mapping Program for 1951 are circumscribed by the gold outline and 2001 outlined in yellow. No 1995 data were available for this system. The 2001 eelgrass coverage was also noted in 2003 in SMAST-MEP sediment surveys and eelgrass beds were observed in Town Cove in 1983 (Teal 1983).

Other factors which influence eelgrass bed loss in embayments can also be at play in the Nauset Estuary, though the recent loss appears completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss could potentially be directly related to mooring density, as the system does support a permanent boat mooring area, however, much of the eelgrass loss has occurred in areas that really do not have boat moorings. While pier construction can cause impacts to eelgrass beds, the number of piers (docks) and the area they represent is insignificant given the area of eelgrass bed loss. It is also important to note that the major eelgrass bed loss was from open water areas as opposed to fringing beds along the shore which would be more susceptible to shading from piers. Boating pressure or small scale shellfishing may be adding additional stress in nutrient enriched areas such as in mid and outer Town Cove, but it does not seem to be the overarching factor, especially given the shallow structure of this basin and the limited navigable water and other ecological indicators that point more towards the effect of nutrient over-enrichment. The pattern of loss is also indicative of a response to nitrogen enrichment. Estuaries, including the Nauset Estuary, support nitrogen gradients due to the highest loading to the most inland basins and tidal hydrodynamic effects. The result is the highest nitrogen levels are typically within the semi-enclosed basins, such as Town Cove, Salt Pond, Wood Cove and Mill Pond. The absence of eelgrass from all of these semi-enclosed basins is consistent with these effects, although only Town Cove has documented eelgrass coverage in the past 60 years. Salt Pond Bay, also falls along the nitrogen gradient, though less enriched than adjacent Salt Pond. The loss of eelgrass from Town Cove and Salt Pond is consistent with the observed chlorophyll and macroalgal accumulations and tidally averaged nitrogen levels, 0.60 mg TN L^{-1} and 0.62 mg TN L^{-1}, respectively. The persistence of the small patch of eelgrass near the main channel to the inlet is likely the result of its proximity to Nauset Inlet and the high quality waters that enter on the flooding tides, which result in a relatively low tidally averaged TN of 0.356 mg L^{-1} and similarly good nutrient related water quality.

It should be noted that the absence of eelgrass from Salt Pond and Mill Pond is in part due to the depth of their central basins and bottom water hypoxia. However, the lack of fringing beds from these basins suggests nitrogen enrichment effects prior to the 1951 MassDEP eelgrass baseline. Unlike these basins, Wood Cove is shallow, but does not support eelgrass habitat due to its dense accumulations of macroalgae. Since eelgrass habitat has not been documented within these 3 basins, they are not to be targeted for restoration. However, restoration of eelgrass habitat in Town Cove and Salt Pond Bay will also result in improvements within these basins.

It is not possible to determine quantitative short- and long-term rates of change in eelgrass coverage from the mapping data, since there is only limited temporal data. However, based upon the 1951 and 1995 coverages, it appears that an area of eelgrass habitat, on the order of ~80 acres, could be recovered if nitrogen management alternatives were implemented (Table VII-3). The historical presence of eelgrass in Town Cove is also supported by observations by WHOI scientists in a 1983 analysis of the Cove (Teal 1983), where eelgrass was observed in the outer portion adjacent the channel. Therefore, it appears that eelgrass was present in Town Cove from 1951 through at least 1983, making its loss recent (1983-2001). It should be noted that the small area of eelgrass that still exists in the system, observed in 2001 and by MEP staff in 2003 is limited to the high quality waters adjacent Nauset Inlet. The presence of even this small region of eelgrass should increase the rate of recovery under reduced nitrogen loading, by providing a source of seeds and propagules within the estuary. Additionally, restoration of eelgrass habitat will necessarily result in restoration of other resources throughout the basins of the Nauset Estuary. With a reduction in nitrogen loading to this system, benthic infaunal habitat would be restored with an increase in shellfish habitat and shift toward larger longer-lived deep burrowing organisms (see below discussion on benthic infaunal community survey).

Based upon the 1951 coverage it appears that nitrogen management to restore eelgrass habitat has the potential to recover a significant resource within this estuary (Table VII-3). Since most of the eelgrass habitat has been lost in the larger basin of Town Cove, it is likely that the smaller enclosed basin such as Salt Pond will see improved habitat quality, as most of the nitrogen entering from the watershed enters first into the semi-enclosed basins before being flushed to the outer portion of the system (Salt Pond Bay and Nauset Harbor).

Table VII-3. Changes in eelgrass coverage in the Nauset Estuary within the Towns of Orleans and Eastham over the past half century (C. Costello).

EMBAYMENT	1951 (acres)	1995 (acres)	2001 (acres)	% Difference (1951 to 2001)
Nauset Estuary	83.40	--	2.04	98%

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 26 locations throughout the Nauset Estuary (Figure VII-11). In some cases multiple samples and assays were conducted at a station. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as key community indices, diversity (H') and evenness (E). It should be noted that, given the loss of eelgrass beds, certain portions of the Nauset Estuary are showing indications of impairment due to nutrient overloading, which will be the focus of restoration efforts. In these areas and especially in areas that are naturally without eelgrass, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Section VIII).

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

Figure VII-11. Aerial photograph of the Nauset Harbor system showing location of benthic infaunal sampling stations (red symbols).

Overall, the infauna survey measured generally diverse and productive benthic animal communities throughout the salt marsh dominated basins and tidal creeks associated with Nauset Marsh and significantly impaired habitat within the nutrient enriched semi-enclosed basins, Town Cove, Salt Pond, Mill Pond and Wood Cove. Except for Wood Cove, these basins are relatively deep (>5m) and all exhibit periodic hypoxia and some anoxia of bottom waters during summer. Wood Cove and the small inner basin of Mill Pond have the additional benthic habitat impairment associated with dense accumulations of macroalgae, *Ulva*, a species associated with watershed nitrogen inputs in many Cape Cod estuaries. These 4 sub-basins currently support significantly impaired benthic animal habitat. Town Cove, Salt Pond and Mill Pond communities are depauperate, with very low species numbers (1-4) distributed among few individuals (36-44) with low diversity (H', 0.7-1.45), and dominated by organic enrichment indicators (tubificids). Any of these indicators is sufficient to classify these habitats as impaired, but combined they indicate a significant impairment of this important resource. The impairment is ultimately due to nitrogen enrichment with tidally averaged TN levels >0.5 mg L^{-1} and proximately due to low summertime oxygen and high rates of organic matter deposition associated with the generated high phytoplankton biomass. Wood Cove is similarly nitrogen enriched (>0.5 mg L^{-1}), but it appears that much of the impairment is related to the dense accumulations of macroalgae, which smother benthic communities. Although the basin has slightly higher numbers of species (6) and individuals (~300) with moderate diversity (H', 2.24), half of the community is represented by well established stress indicator species and the remainder, organic tolerant species, indicating a significant level of habitat impairment (Table VII-4).

In contrast the salt marsh dominated areas of the lagoon of Nauset Marsh, inclusive of Salt Pond Bay and Nauset Bay, currently support benthic animal communities associated with high quality salt marsh benthic habitat. The salt marsh dominated open water basins of the Bays have moderate numbers of species (10-12) with high numbers of individuals (>1000) with moderate to high diversity (H', 2.4-2.8) and evenness (E, 0.7 - 0.9), with few stress indicator species in low numbers. Equally important the communities are dominated by crustaceans, mollusks and polychaetes, typical of high quality wetland benthic habitat. Given the strong salt marsh influences on these basins, which tend to reduce species numbers and diversity even in "pristine" systems, it appears that these salt marsh basins are not showing indications of excessive nutrient enrichment and are currently supporting high quality habitat. It should be noted that salt marshes are naturally nutrient and organic matter enriched and the benthic animal communities found within these basins are consistent with salt marsh influenced systems throughout the region. Similarly, the main creeks (tidal channels) do not appear to be impaired by nitrogen enrichment, although they have fewer species and numbers than the bays. The creeks do generally support only few stress indicator species, except in the region directly influenced by Mill Pond outflows, which has high numbers of tubificids (as does the directly adjacent lower reach of Mill Pond. The central and outer creeks of Nauset Marsh appear to have shifting sediments due to the very high tidal velocities. Sand waves are common as are shifting sand bars. The MEP has encountered similar conditions in other high velocity channels, with the similar finding of a reduced benthic community, composed of non-organic stress indicators. In these regions the community appears to be structured primarily by the unstable sediments, rather than effects associated with watercolumn conditions (nitrogen, oxygen, chlorophyll).

It appears that while the semi-enclosed open water basins are exhibiting impaired benthic animal habitat due to nitrogen enrichment, the large outer lagoon (Nauset Marsh) is supporting high quality benthic animal habitat, particularly when the ecological structure of the estuarine basin is taken into account (e.g. salt marsh influences). Classification of habitat quality necessarily included the structure of the estuarine basin, specifically that it is fully representative of a tidal embayment (e.g. Town Cove), as opposed to a tidal river or salt marsh basin. The Nauset Estuary is a complex estuary composed of 3 types of basins: tidal embayments (open water basins with little associated salt marsh), salt marsh ponds (salt marsh dominated open basins) and salt marsh tidal creeks (tidal channels through emergent salt marsh). Each of these 3 basin types has different natural sensitivities to nitrogen enrichment and organic matter loading and each has its own benthic community indicative of an unimpaired or impaired habitat. Evaluation of infaunal habitat quality considered the natural structure of each system and the types of infaunal communities that they support. The benthic animal communities associated with the salt marsh basins indicated generally healthy infaunal habitat, consistent with the tidally averaged nitrogen levels and levels of oxygen depletion in line with the ecosystem types represented. The general absence of macroalgal accumulations and sediments of consolidated sands and mud, with a visible oxidized surface layer is also consistent with the community measurements. The salt marsh tidal creeks also did not indicate impairment by watershed nitrogen loading, but appear to have infaunal communities structured by the unconsolidated unstable sediments and high velocity tidal currents. In contrast, the tidal embayments (semi-enclosed basins) are currently supporting impaired benthic animal habitat associated with nitrogen enrichment. Town Cove historically supported much of the system's eelgrass habitat, but that has also been lost (1983-2001). Since eelgrass loss has occurred in the inner and mid reach of Town Cove indicating a significant level of impairment to eelgrass habitat, lowering the nitrogen to improve eelgrass habitat in this region will also likely be sufficient to restore infaunal animal habitat throughout this basin, as eelgrass is much more sensitive to nitrogen enrichment than infaunal communities. Restoration of benthic animal habitat in areas not historically supporting eelgrass will require additional targeted reductions in nitrogen levels (Section VIII).

Table VII-4. Benthic infaunal community data for the Nauset Estuary. 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 m^2). Station i.d.'s refer to figure VII-11.

Basin	Total Actual Species	Total Actual # Indiv.	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)	N	Station i.d.
Nauset Bay	10	1381	10	2.82	0.87	4	27,28
Salt Pond Bay	12	1464	10	2.42	0.68	4	1,SPB-1,SPB-2
Nauset Marsh	5	288	5	1.47	0.69	6	51,52,20,SI
Nauset Inlet	2	13	N/A	0.62	0.62	1	53
Town Cove- Inner	2	36	2	0.66	0.77	10	10,10N,10S,12 13,13N,13S
- Mid	4	198	4	1.45	0.81	4	16,16N; 17
- Out	3	44	N/A	1.09	0.82	2	19
Salt Pond	2	40	3	0.75	0.89	3	25, SP3
Wood Cove	6	284	6	2.24	0.90	2	22
Mill Pond - Main	1	16	N/A	1.00	1.00	2	29
- Outer	12	741	11	3.11	0.88	2	30

Other Resource Characteristics:

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection and as available, other biological resources assessments developed by the

Commonwealth were integrated into the habitat assessment portion of the MEP nutrient threshold development process. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the propagation of shellfish (Figure VII-12a,b,c). Unlike many of the systems on Cape Cod, all of the enclosed waters of the Nauset Estuary are classified as approved for the taking of shellfish year round, indicating the system is not impaired relative to the taking of shellfish. This is most likely due to lower levels of development in the watershed to the overall system as well as the tide range and flushing of the system. Bacterial concerns in an estuary are typically the result of both human activity (septic systems in the watershed) as well as natural fauna.

Given the quality of the shellfish habitat, the Nauset Estuary has also been classified as supportive of specific shellfish communities (Figure VII-13). The major shellfish species with potential habitat within the Nauset Estuary are mainly quahogs (*Mercenaria*) with smaller areas suitable for bay scallops. Additionally, suitable habitat closer to shore and along the various marsh islands was identified for soft shell clams (*Mya*) as well as razor clams and blue mussels. It should be noted that the observed pattern of shellfish suitability is consistent with the observed organic rich sediments within the Nauset Estuarine System. Moreover, improving eelgrass and benthic animal habitat quality should also expand the shellfish growing area within this system.

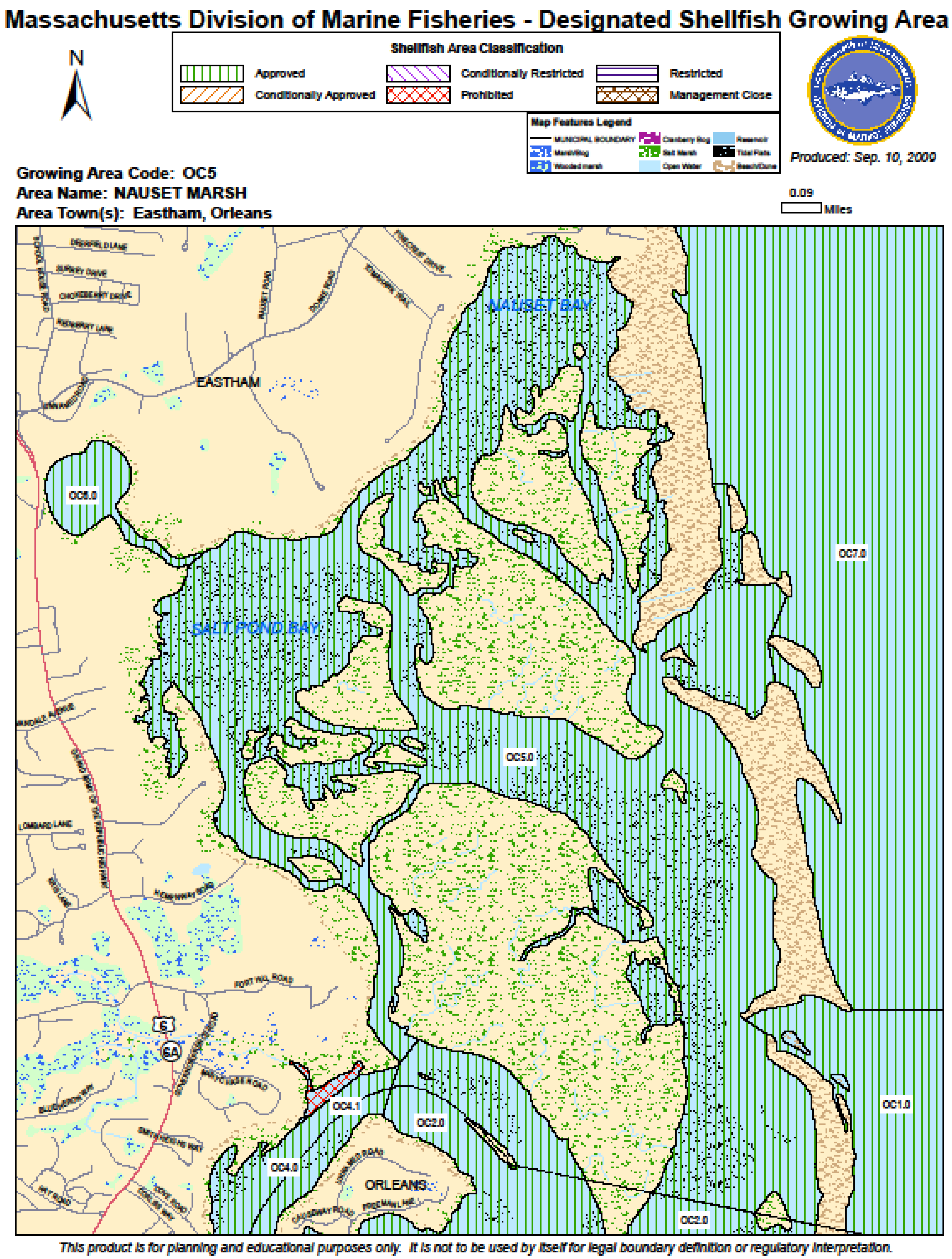


Figure VII-12a. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

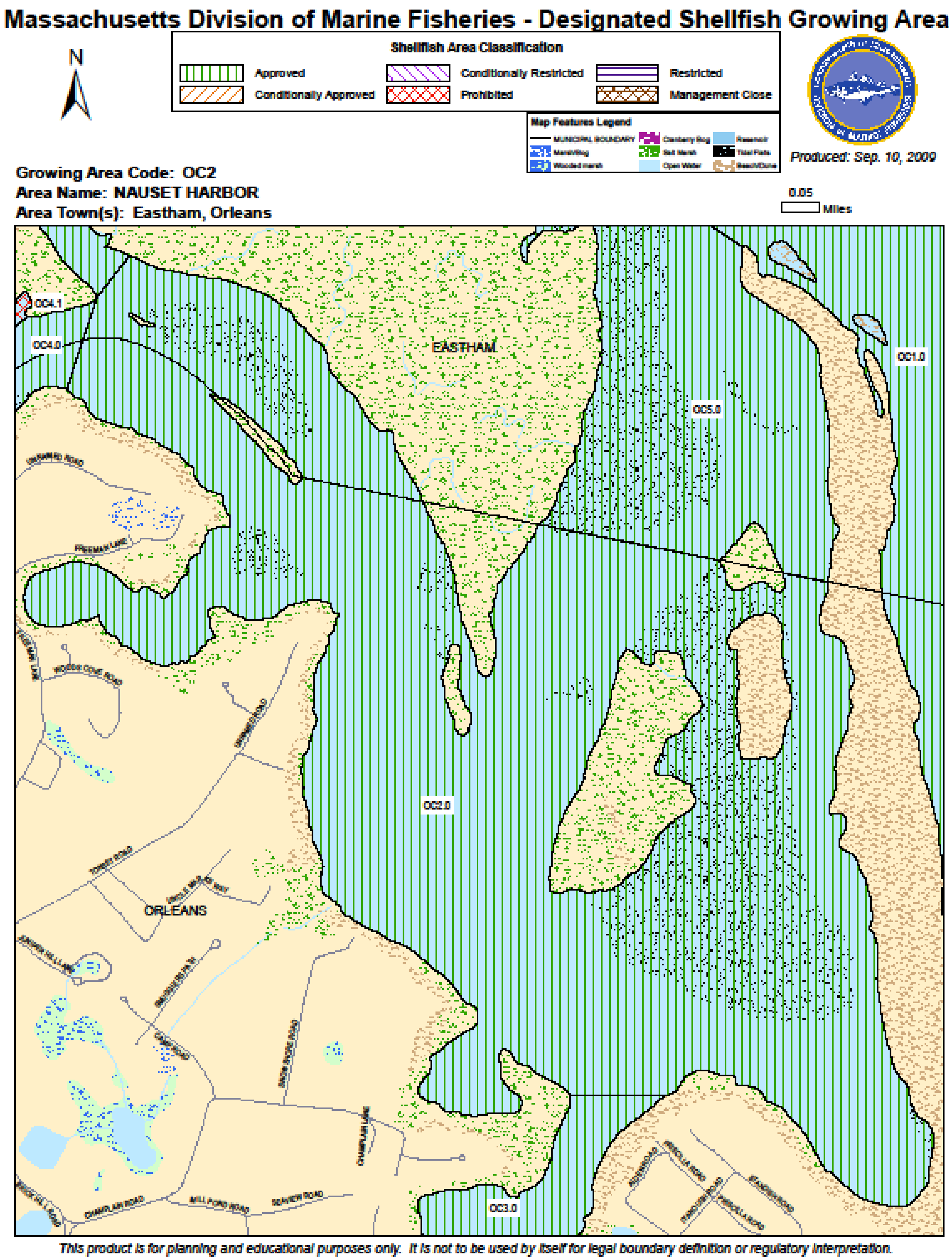


Figure VII-12b. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

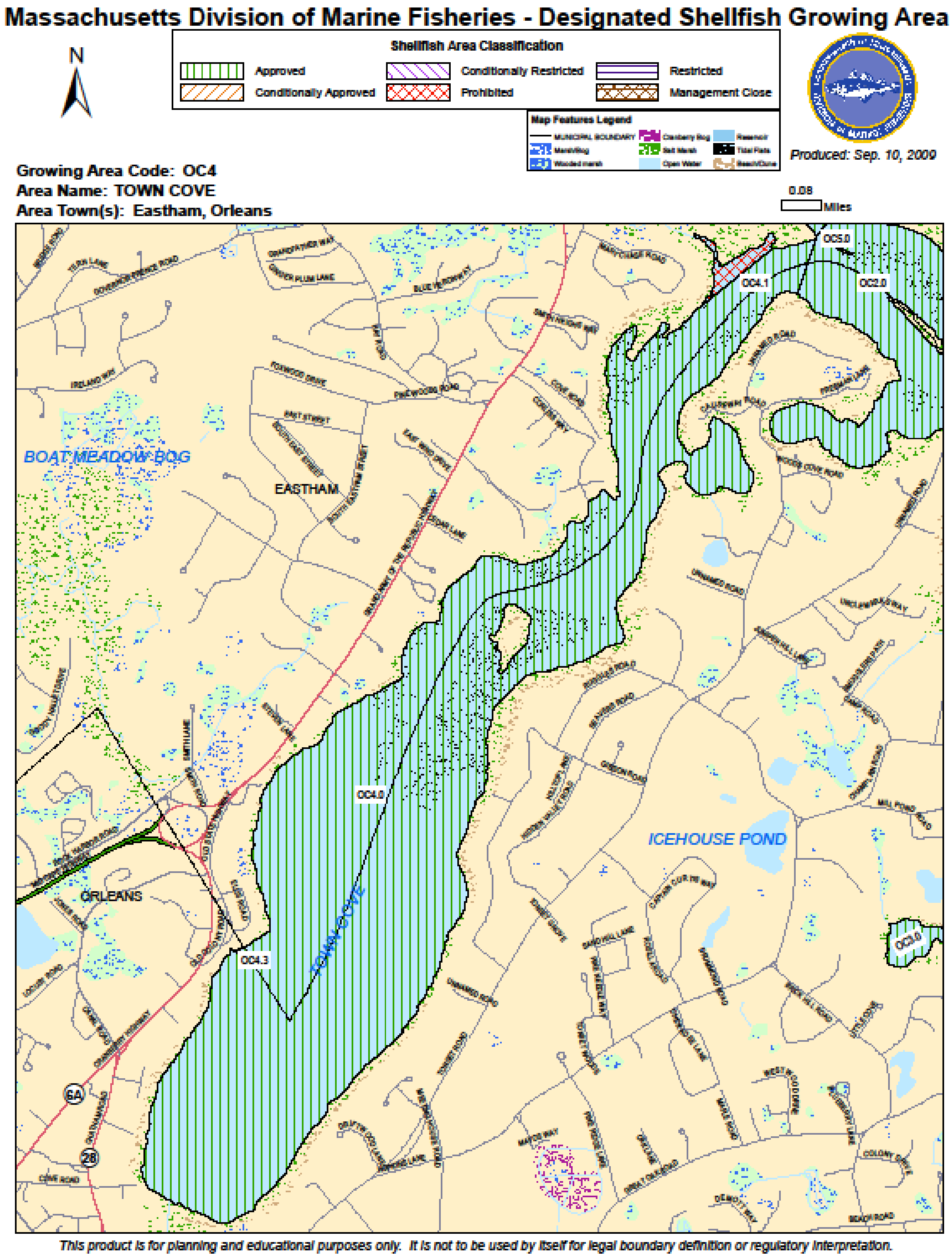


Figure VII-12c. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

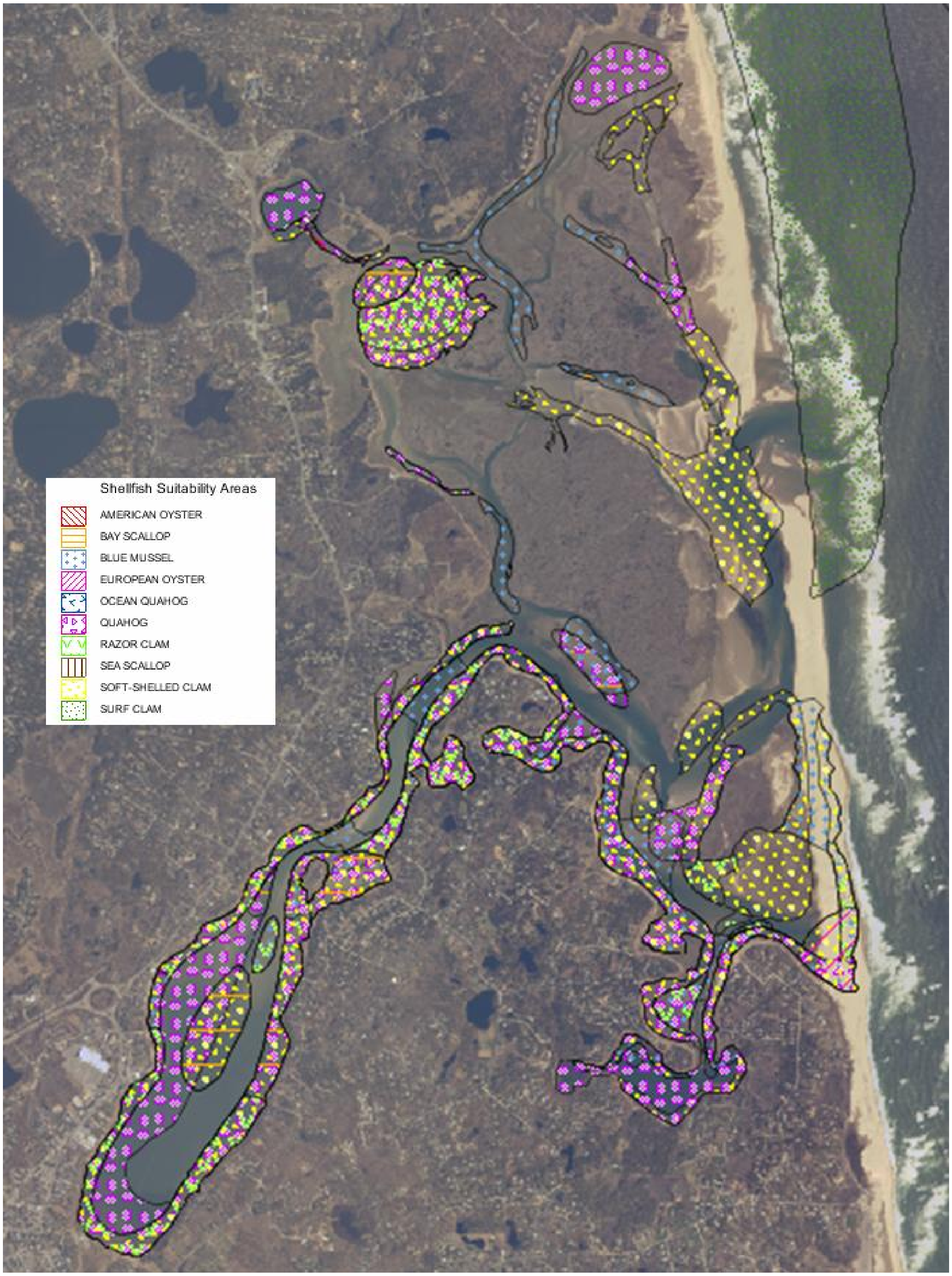


Figure VII-13 Location of shellfish suitability areas within the Nauset Harbor Estuary as determined by Mass Division of Marine Fisheries. The predominant shellfish in a fully functional habitat are quahogs and soft shell clams. However, bay scallops could also return under nitrogen management, as eelgrass habitat would be restored. Suitability does not necessarily mean that the species of shellfish is "present".

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

The determination of site-specific nitrogen thresholds for an estuary requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll). Additional information on temporal changes within each component sub-basin and its associated watershed nitrogen load further strengthen the analysis. These data were collected to support threshold development for the Nauset Estuary by the MEP and were discussed in Section VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline Orleans Water Quality Monitoring Program.

The Nauset Estuary is a complex estuary composed of 3 types of basins: tidal embayments (open water basins with little associated salt marsh) such as Town Cove, Salt Pond, Wood Cove, and Mill Pond; salt marsh ponds (salt marsh dominated open basins) such as Salt Pond Bay and Nauset Bay; and salt marsh tidal creeks with high tidal velocities and areas of shifting sands (tidal channels through emergent salt marsh) within Nauset Marsh. Each of these 3 basin types has different natural sensitivities to nitrogen enrichment and organic matter loading and each has its own benthic community indicative of an unimpaired or impaired habitat. The MEP evaluation of habitat quality considered the natural structure of each system and the types of infaunal communities and eelgrass coverages that they support under low and high levels of nitrogen enrichment. Currently, the Nauset Estuary is showing differences in nitrogen enrichment and habitat quality among its various component basins (Table VIII-1).

Table VIII-1. Summary of nutrient related habitat quality within the Nauset Estuary within the Towns of Orleans and Eastham, MA, based upon assessments in Section VII. Nauset Marsh is a large shallow salt marsh filled basin, with associated salt marsh open water areas of Nauset Bay and Salt Pond Bay; tributary to the main salt marsh are typical semi-enclosed embayments: Town Cove, Salt Pond, Wood Cove and Mill Pond. Note: WQMP refers to the Orleans Water Quality Monitoring Program.

Health Indicator	Nauset Estuary						
	Nauset Marsh			Town Cove	Salt Pond	Wood Cove	Mill Pond
	Nauset Marsh	Nauset Bay	Salt Pond Bay				
Dissolved Oxygen	**H[1]**	**H[1]**	**H[1]**	**SI[2]**	**SI[3]**	**MI/SI[4]**	**MI-SI[5]**
Chlorophyll	**H[6]**	**H[6]**	**H[6]**	**MI-SI[8]**	**MI[7]**	**H[9]**	**MI-SI[8]**
Macroalgae	**--[10]**	**--[10]**	**MI[11]**	**MI[11]**	**--[10]**	**MI[13]**	**SI[12]**
Eelgrass	**H/MI[14]**	**--[15]**	**SI[16]**	**SI[16]**	**--[15]**	**--[15]**	**--[15]**
Infaunal Animals	**H[17]**	**H[18]**	**H[18]**	**SI[19]**	**SI[20]**	**SI[21]**	**SI[20]**
Overall:	**H[22]**	**H[23]**	**SI[24]**	**SI[25]**	**SI[26]**	**SI[27]**	**SI[26]**

See notes below

1 - Nauset Marsh: a salt marsh dominated lagoon, oxygen depletion rarely to ≤4 mg/L generally >5mg/L, marsh near inlet
typically >6 mg L-1, WQMP; extensive tidal salt marsh results in natural organic enrichment & natural oxygen depletion
observed oxygen levels are relatively high for a salt marsh and salt marsh dominated open water basins (>5 mg/L),
WQMP, high quality habitat.
2 - main basin: oxygen depletion typically <4 mg/L (55% of record), frequently <3 mg/L (38%), periodic anoxia.
3 - mid-depth: oxygen depletions generally <5 mg/L (61% of record), frequently <4 mg/L (29%), periodic decline to <3 mg/L
(4% of record); deep water: periodic anoxia;
4- oxygen levels depleted to <5 mg/L 20% of record, <4 mg/L 7%, periodically 1 mg L^{-1}, large daily excursions 4-6 mg L^{-1}.
5 - mid-depth: oxygen depletions generally >5 mg/L not declining to 4 mg/L; deep waters periodically anoxic
6 - low summer chlorophyll levels averaging <4 ug/L at all 6 stations, 2001-04, WQMP.
7 - moderate summer chlorophyll levels averaging 6.8 ug/L, blooms >10 ug/L ~20% of record and >20 ug/L ~5%
8 - moderate/high chlorophyll levels, averaging 9-11 ug/L, >10 ug/L >48%-28% of record, blooms >20 ug/L, 8%-3%
9 - low chlorophyll, averaging 4 ug/L over 18 sampling events, 2001-2003 WQMP
10 - drift algae sparse or absent
11 - patchy accumulations of *Ulva*.
12 - dense accumulation of *Ulva*, in innermost basin.
13 - moderate accumulations of filamentous algae.
14 - small bed in channel adjacent Nauset Inlet in 2001 & 2003, moderate loss of coverage post-1951
15 - no evidence this basin is supportive of eelgrass.
16 - MassDEP indicates significant loss of eelgrass coverage, 1951-2001, absence confirmed 2003 MEP.
17 - Infauna: low numbers of species (5) and diversity (H', 1.47), high Evenness (0.7); moderate # of individuals (288),
few stress indicator species, community affected by sediment transport, similar to other high velocity channels.
18 - Infauna: high numbers of individuals (>1000), moderate species (10-12), moderate diversity (2.4-2.8) and high Evenness (0.68-0.83); organic enrichment indicators typical of salt marsh influenced basins, dominated by crustaceans, mollusks & polychaetes, very few stress indicator species.
19 - Infauna: very low numbers of species (2-4) and diversity (H', 0.66-1.45); low number of individuals (36-198), dominated by opportunistic organic enrichment indicators (tubificids) generally >70% of community, indicative of a significantly impaired habitat, consistent with nitrogen enrichment.
20 - Infauna: few species (<2) and individuals (<40), as a result of periodic hypoxia/anoxia.
21 - Infauna: low number of species (6) and diversity (H'= 2.24) moderate numbers of individuals (~300), dominated by organic enrichment indicators (tubificids, Capitella)
22 - Generally high quality, with Moderate Impairment due to the partial loss of eelgrass in the southern reach (MassDEP). The generally low chlorophyll a and lack of significant oxygen depletion and macroalgae are consistent with the productive benthic communities, except near outer Mill Pond.
23 - High Quality salt marsh dominated basin, oxygen depletion, low summer chlorophyll a levels & sparse macroalgae
consistent with productive benthic communities without stress indicators.
24 - Significant Impairment, indicated by eelgrass loss with patchy macroalgal accumulations (*Ulva,* indicative of nitrogen enrichment), but chlorophyll and oxygen are consistent with the generally high quality infauna habitat, except in areas of macroalgal accumulation.
25 - Significant Impairment resulting from significant loss of eelgrass coverage coupled with high chlorophyll levels and loss of benthic animal habitat consistent with measured low dissolved oxygen.
26 - Significant Impairment resulting from loss of benthic animal habitat, periodic hypoxia at mid depths (anoxia at deeper depths) and moderate chlorophyll.
27 - Significant Impairment: benthic animal community with low species and moderate numbers dominated by organic enrichment indicators, moderate accumulations of macroalgae and periodic DO to 1 mg L-1
28 - Significant Impairment: resulting from loss of benthic animal habitat, periodic hypoxia at mid depths (anoxia at deeper depths) with moderate to high chlorophyll levels; dense accumulation of macroalga (*Ulva*) in innermost basin.
H = healthy habitat conditions; MI = Moderate Impairment; SI = Significant Impairment;
SD = Severe Degradation; -- = not applicable to this estuarine reach

At present, eelgrass has nearly disappeared from the Nauset Estuary, with only a small area remaining adjacent Nauset Inlet. The observed loss is consistent with the level of nitrogen enrichment and tidal flows within this system and clearly indicates impairment of this resource. The overall pattern of eelgrass distribution and temporal decline in coverage is fully consistent with the spatial pattern of nitrogen enrichment (Section VI) and oxygen and chlorophyll levels in the various basins (Section VII). The pattern of decline is typical of environmental changes wrought by nutrient enrichment. Nutrient enrichment tends to result in loss of eelgrass habitat in the more tidally restricted basins (e.g. Town Cove), which also tend to be the focus areas for watershed nitrogen inputs. Salt Pond Bay exists along this nitrogen gradient, though less enriched than Town Cove. The pattern of loss from the tidal reaches furthest from the inlet can also be seen in the Nauset Harbor System, where the remaining eelgrass is adjacent the main inlet. This pattern parallels the gradient in nitrogen enrichment of these estuarine waters.

The loss of eelgrass from Town Cove and Salt Pond is consistent with the observed chlorophyll and macroalgal accumulations and tidally averaged nitrogen levels, 0.60 mg TN L^{-1} and 0.62 mg TN L^{-1}, respectively. The persistence of the small patch of eelgrass near the main channel to the inlet is likely the result of its proximity to Nauset Inlet and the high quality waters that enter on the flooding tides and results in a relatively low tidally averaged TN of 0.36 mg L^{-1} and similarly high nutrient related water quality.

It should be noted that the absence of eelgrass from Salt Pond and Mill Pond is in part due to the depth of their central basins and bottom water hypoxia. However, the lack of fringing beds from these basins suggests nitrogen enrichment effects prior to the 1951 MassDEP eelgrass baseline. Unlike these basins, Wood Cove is shallow, but does not support eelgrass habitat due to its dense accumulations of macroalgae. Since eelgrass habitat has not been documented within these 3 basins, they are not to be targeted for restoration. However, restoration of eelgrass habitat in Town Cove and Salt Pond Bay will also result in improvements within these basins.

Based upon the documented loss of eelgrass coverage from Town Cove and Salt Pond Bay, consistent with the effects associated with watershed nitrogen loading and the enrichment of the waters of these basins, both basins are classified as significantly impaired for eelgrass habitat. This classification indicates that restoration related to nitrogen loading impacts within the Nauset Estuary needs to focus on lowering nitrogen levels within these basins to support eelgrass survival and growth. Benthic animal habitat was used as the key indicator of estuarine impairment for the other basins not historically supporting eelgrass coverage.

Overall, the infauna survey measured generally diverse and productive benthic animal communities throughout the salt marsh dominated basins and tidal creeks associated with Nauset Marsh and significantly impaired habitat within the nutrient enriched semi-enclosed basins, Town Cove, Salt Pond, Mill Pond and Wood Cove. Except for Wood Cove, these basins are relatively deep (>5m) and all exhibit periodic hypoxia and some anoxia of bottom waters during summer. Wood Cove and the small inner basin of Mill Pond have the additional benthic habitat impairment associated with dense accumulations of macroalgae, *Ulva*, a species associated with watershed nitrogen inputs in many Cape Cod estuaries. These 4 sub-basins currently support impaired benthic animal habitat. Town Cove, Salt Pond and Mill Pond communities are depauperate, with very low species numbers (1-4) distributed among few individuals (36-44) with low diversity (H', 0.7-1.45), dominated by organic enrichment indicators (tubificids). Any of these indicators is sufficient to classify these habitats as impaired, but combined they indicate that a classification of Significant Impairment of this important resource is appropriate. The impairment is ultimately due to nitrogen enrichment with tidally averaged TN levels >0.5 mg L^{-1} and proximately due to low summertime oxygen and high rates of organic matter deposition associated with the generated high phytoplankton biomass. Wood Cove is similarly nitrogen enriched (>0.5 mg L^{-1}), but it appears that much of the impairment is related to the dense accumulations of macroalgae which smother benthic communities. Although this basin has slightly higher numbers of species (6) and individuals (~300) with moderate diversity (H', 2.24), half of the community is represented by well established stress indicator species and the remainder, organic tolerant species, indicating a significant level of habitat impairment (Table VII-4).

In contrast the salt marsh dominated areas of the lagoon of Nauset Marsh, inclusive of Salt Pond Bay and Nauset Bay, currently support benthic animal communities associated with high quality salt marsh benthic habitat, without notable nitrogen related impairments. The salt marsh dominated open water basins of the Bays have moderate numbers of species (10-12) with high numbers of individuals (>1000) with moderate to high diversity (H', 2.4-2.8) and evenness (E, 0.7 - 0.9), with few stress indicator species in low numbers. Equally important the communities are dominated by crustaceans, mollusks and polychaetes, typical of high quality wetland benthic habitat. Given the strong salt marsh influences on these basins, which tend to reduce species numbers and diversity even in "pristine" systems, it appears that these salt marsh basins are not showing indications of excessive nutrient enrichment and are currently supporting high quality habitat. It should be noted that salt marshes are naturally nutrient and organic matter enriched and the benthic animal communities found within these basins are consistent with salt marsh influenced systems throughout the region. Similarly, the main creeks (tidal channels) do not appear to be impaired by nitrogen enrichment, although they have fewer species and numbers than the bays. The creeks do generally support only few stress indicator species, except in the region directly influenced by Mill Pond outflows. The central and outer creeks of Nauset Marsh appear to have shifting sediments due to the very high tidal velocities. Sand waves are common as are shifting sand bars. The MEP has encountered similar conditions in other high velocity channels, with the similar finding of a reduced benthic community, composed of non-organic stress indicators. In these regions the community appears to be structured primarily by the unstable sediments, rather than effects associated with water column conditions (nitrogen, oxygen, chlorophyll).

It appears that while the semi-enclosed open water basins are exhibiting impaired benthic animal habitat due to nitrogen enrichment, the large outer lagoon (Nauset Marsh) is supporting high quality benthic animal habitat, particularly when the ecological structure of estuarine basin is taken into account (e.g. salt marsh influences), see Table VII-4. Classification of habitat quality necessarily includes the structure of the estuarine basin, specifically that it is fully representative of a tidal embayment (e.g. Town Cove), as opposed to a tidal river or salt marsh basin. Evaluation of infaunal habitat quality considered the natural structure of each system and the types of infaunal communities that they support. The benthic animal communities associated with the salt marsh basins indicated generally healthy infaunal habitat, consistent with the tidally averaged nitrogen levels and levels of oxygen depletion in line with the ecosystem types represented. The general absence of macroalgal accumulations and sediments of consolidated sands and mud, with a visible oxidized surface layer is also consistent with the community measurements. The salt marsh tidal creeks also did not indicate impairment by watershed nitrogen loading, but appear to have infaunal communities structured by the unconsolidated unstable sediments and high velocity tidal currents. In contrast, the tidal embayments (semi-enclosed basins) are currently supporting impaired benthic animal habitat associated with nitrogen enrichment. Town Cove historically supported much of the system's eelgrass habitat, but that has also been lost (1983-2001), as has the less extensive eelgrass coverage in Salt Pond Bay. Since eelgrass loss has occurred in the inner and mid reach of Town Cove indicating a significant level of impairment to eelgrass habitat, lowering the nitrogen to improve eelgrass habitat in this region will also likely be sufficient to restore infaunal animal habitat throughout this basin, as eelgrass is much more sensitive to nitrogen enrichment than infaunal communities.

Based upon the above analysis, eelgrass habitat was selected as the primary nitrogen management goal for the Nauset Estuary, specifically within Town Cove and Salt Pond Bay. Analysis of the 1951 and 2001 coverages indicates that an area of eelgrass habitat, on the order of ~80 acres, could be recovered if nitrogen management alternatives were implemented (Table VII-3). In addition, it should be noted that the presence of the small region of eelgrass near Nauset Inlet should increase the rate of eelgrass recovery under reduced nitrogen loading, by providing a source of seeds and propagules within the estuary.

Given the greater sensitivity of eelgrass to nitrogen enrichment compared to infaunal habitat, restoring eelgrass should also result in mitigating nitrogen related impairment of benthic habitats, specifically, restoration of impaired infaunal habitat within each of the semi-enclosed basins (Town Cove, Salt Pond, Mill Pond, Wood Cove). While it is recognized that the deepest portions of Salt Pond and Mill Pond will likely continue to support impaired habitat due to their basin configuration and depth (>6 meters), impairment of the shallower adjacent areas should be secondary targets for restoration. With a reduction in nitrogen loading to Town Cove and Salt Pond Bay to restore eelgrass habitat, the benthic infaunal habitat throughout the Nauset Estuary would be restored with an increase in shellfish habitat and shift toward larger longer-lived deep burrowing organisms. However, to ensure that restoration of benthic animal habitat in areas not historically supporting eelgrass will occur, secondary targets need to be established that may require small additional targeted reductions in nitrogen levels. These goals are the focus of the MEP threshold analysis presented in Section VIII.3.

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

The significant impairment of eelgrass habitat within Town Cove and Salt Pond Bay, as indicated by the complete loss of coverage associated with nitrogen enrichment (Section VII.3, VIII.1), makes the primary restoration target for the Nauset Estuary eelgrass restoration. At present, eelgrass has been virtually lost from the Nauset Estuary, with only a small bed remaining within the main creek to Nauset Inlet. The loss of eelgrass within the inner basins is consistent with both the increase in watershed nitrogen loading to this system, the pattern of nitrogen related eelgrass loss, the observed nitrogen levels with resultant macroalgal accumulations in Salt Pond Bay and elevated chlorophyll and dissolved oxygen depletions in Town Cove. The remaining eelgrass is associated with high nitrogen related water quality.

While the remaining eelgrass within the Nauset Estuary is found at tidally averaged TN levels of 0.36 mg L^{-1}, this does not represent the nitrogen "threshold" level for eelgrass in this system. First, the site is generally deeper than the historic eelgrass areas in Town Cove and Salt Pond Bay, and therefore requires a lower nitrogen level to support eelgrass. Second, a threshold represents the level at which eelgrass is sustainable, but if nitrogen increases, eelgrass begins to decline. At present, we only know that this site is relatively stable. More detailed conclusions cannot be made because the required temporal analysis is not available. The result is that it can be concluded that the nitrogen threshold for eelgrass in the inner basins should not be lower than 0.36 mg L^{-1}. However, with this limited temporal data and by making defensible comparisons to other similar estuarine basins, the nitrogen threshold can be refined.

Highly productive and stable eelgrass beds within the Westport River provide one comparison. The MEP has documented loss of eelgrass within the mid reach of the East Branch at tidally averaged TN levels of >0.506 and moderate habitat impairment in the West Branch (dense colonization by epiphytes) at levels >0.50 mg L-1. Areas with TN levels of 0.64 mg L^{-1} (East Branch) had no history of supporting eelgrass beds. In contrast healthy eelgrass beds in the lower portion of the East Branch were observed at present levels ~0.42-0.43 mg N

L-1. The tidally averaged level of TN supportive of high quality eelgrass habitat in this estuary is therefore between 0.43 - 0.50 mg N L-1.

High quality eelgrass in Cape Cod estuaries has been similarly documented by the MEP. TN levels supportive of eelgrass habitat within relatively deep systems (>2 m) like Stage Harbor (0.38 mg L-1) or West Falmouth Harbor and Phinneys Harbor (0.35 mg L-1) yield similar levels compared to the deep channel with remaining eelgrass in the Nauset Estuary. However, as the historic eelgrass habitat in Town Cove and Salt Pond Bay are in shallow water, with eelgrass generally at <1 m depth, eelgrass beds are sustainable at higher TN (higher chlorophyll) levels than in deeper waters because of the "thinner" water column that light has to pass through to support eelgrass growth (less water to penetrate). At comparable depths in the Bournes Pond Estuary (Falmouth), eelgrass has historically been confined to the lower estuarine basin and that system has nitrogen concentrations of 0.45 mg TN L^{-1} which supportive of eelgrass growing at shallow depths. Within the main open water stem of the channel to the upper portion of the Bournes Pond estuary, eelgrass is supported in deeper water at a nitrogen concentration of 0.42 mg TN L^{-1}. Further within the main channel region of Bournes Pond, the system supports healthy eelgrass beds at tidally averaged TN concentrations of 0.426 mg TN L^{-1} and has eelgrass in patches (not beds & not high quality) at tidally averaged TN of 0.481 mg TN L^{-1}. Additionally, within the lower reach of the Green Pond Estuary, sparse eelgrass is found at tidally averaged TN levels of 0.41 mg TN L^{-1}. Similarly the threshold tidally averaged TN level for restoration of eelgrass in the lower Parker's River was 0.45 mg TN L^{-1}, but only shallow water beds were targeted due to the basin configuration. It should be added that eelgrass can persist at nitrogen levels that are non-supportive of healthy beds as is the case with eelgrass within Hamblin Pond which persists at a high TN level (0.5 mg TN L^{-1}), even after eelgrass within the central portion of Waquoit Bay had disappeared. However, the 0.5 mg TN L^{-1} level was associated with diminishing eelgrass patches and was just beyond the level supportive of high quality habitat. These higher levels (>0.5 mg L-1) were also associated with loss of eelgrass areas in the Nauset Estuary (and Westport River). Synthesis of the available eelgrass and nitrogen data indicates that the threshold nitrogen level to support high quality stable eelgrass habitat within the historic coverage areas of the Nauset Estuary is >0.36 mg L^{-1} (level in the remaining bed) but <0.50 mg L^{-1}, since areas of eelgrass loss in the Nauset Estuary have levels >0.50 mg L^{-1}. Comparison to other systems indicates similar findings, but with high quality habitat at 0.45 mg L^{-1} (Bournes Pond, Parkers River), 0.43 mg L^{-1} (Westport River), but impaired habitat at TN levels of 0.48 mg L^{-1} (Bournes Pond), and 0.50 mg L^{-1} (Waquoit Bay, Westport River, Bass River).

Based upon the above analysis a single sentinel station was selected at the long term monitoring station in Town Cove, WMO-27 (at the uppermost edge of the main historic bed), for the re-establishment of the expansive beds at this location and in the region between this station and outer impaired areas, as well as the fringing beds at the head of the Cove. This determination is directly linked to analysis of the historical eelgrass coverage. The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location was determined to be 0.45 mg TN L^{-1}, with a secondary check to lower the Salt Pond Bay TN level to <0.45 mg N L^{-1}. As there has not been significant eelgrass habitat within the Nauset Estuary for over a decade, this threshold was based upon analysis of remaining eelgrass beds and comparison to other local embayments of similar depths and structure under MEP analysis.

Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fisheries resources), benthic infaunal habitat quality must also be supported as a secondary condition. Benthic animals are more tolerant of nutrient and organic matter enrichment than eelgrass, which requires clear waters and high oxygen levels.

At present, in the regions with moderately to significantly impaired infaunal habitat within the Nauset Estuary, tidally averaged total nitrogen (TN) levels of 0.51 to 0.62 mg TN L^{-1} were observed by the monitoring program. The observed level of impairments within Town Cove, 0.53-0.60 mg N L^{-1} (tidally averaged), Wood Cove, 0.51 mg N L^{-1}, mid-upper region of both Salt Pond, 0.62 mg N L^{-1} and Mill Pond, 0.51-0.60 mg N L^{-1}, are consistent with observations by the MEP Technical Team in other enclosed basins in southeastern Massachusetts (e.g. Perch Pond, Bournes Pond, Popponesset Bay, Stage Harbor, Westport River) where levels <0.5 mg N L^{-1} were found to be supportive of healthy infaunal habitat and where moderately impaired habitat was found at ~0.6 mg TN L^{-1}. As another example, the Centerville River system showed moderate impairment at tidally averaged TN levels of 0.526 mg N L-1 in Scudder Bay (salt marsh dominated) and at 0.543 mg TN L-1 in the middle reach of the Centerville River. Similarly, moderate impairment was also observed at TN levels (0.535-0.600 mg TN L^{-1}) within the Wareham River.

Based upon these observations, the MEP Technical Team concluded that an upper limit of 0.50 mg N L^{-1} tidally averaged TN would support healthy infaunal habitat in the semi-enclosed embayment basins of the Nauset Estuary. This represents a secondary threshold as achieving the primary nitrogen threshold, 0.45 mg L^{-1}, to restore eelgrass in Town Cove and Salt Pond Bay, will likely lower nitrogen levels within the semi-enclosed, as well. It should be emphasized that these secondary criteria values were not used for setting the primary nitrogen threshold in this estuarine system. These secondary targets merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station within Town Cove. The results of the Linked Watershed-Embayment modeling are used to ascertain that when the nitrogen threshold is attained, TN levels in these regions are also within the acceptable range. The goal is to achieve the nitrogen target at the sentinel location and restore eelgrass habitat within Town Cove and Salt Pond and restore infaunal habitat throughout the System. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations 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 infaunal habitats in the Nauset Harbor estuary 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 lowered by reductions in septic effluent discharges until the nitrogen levels reached the threshold level at the sentinel station chosen for the Nauset Harbor estuary system. It is important to note that load reductions can be produced by reduction of any or all sources. 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 restoration of this nitrogen impaired embayment. A comparison between present septic and total watershed loading and the loadings for the modeled threshold scenario is provided in Tables VIII-2 and VIII-3.

Table VIII-2. Comparison of sub-embayment watershed septic loads (attenuated) used for modeling of present and threshold loading scenarios of the Nauset Estuary. 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 septic load (kg/day)	threshold septic load % change
Nauset Marsh	8.20	8.20	0.0%
Salt Pond	3.82	0.00	-100.0%
Wood Cove	0.60	0.60	0.0%
Mill Pond	4.02	4.02	0.0%
Rachel Cove	0.14	0.14	0.0%
Town Cove	24.27	6.07	-75.0%
Nauset Stream	1.90	0.47	-75.0%
System Total	42.95	19.51	-54.6%

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required 55% removal of septic load (associated with direct groundwater discharge to the embayment) for the entire system. This load is being removed from the Town Cove and Salt Pond watersheds. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. For example, removal of 75% of the septic load from the Town Cove watershed results in a 67.2% reduction in total watershed nitrogen load within the Town Cove watershed. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent 'worst-case' summertime conditions.

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 Nauset Estuary. 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 load (kg/day)	threshold % change
Nauset Marsh	10.73	10.73	0.0%
Salt Pond	5.01	1.19	-76.1%
Wood Cove	0.75	0.75	0.0%
Mill Pond	4.93	4.93	0.0%
Rachel Cove	0.18	0.18	0.0%
Town Cove	29.20	9.57	-67.2%
Nauset Stream	2.39	0.96	-59.8%
System Total	53.19	29.75	-47.1%

Table VIII-4. Threshold sub-embayment loads used for total nitrogen modeling of the Nauset Estuary, 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)
Nauset Marsh	10.73	11.25	46.84
Salt Pond	1.19	0.30	14.20
Wood Cove	0.75	0.24	4.66
Mill Pond	4.93	1.07	3.22
Rachel Cove	0.18	0.16	0.00
Town Cove	9.57	5.23	41.52
Nauset Stream	2.39	--	--
System Total	29.75	18.25	110.44

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN total watershed load of 47% are required in the system.

Although the above modeling results provide one manner of achieving the selected threshold level for the sentinel site within the estuarine system, the specific example does not represent the only method for achieving this goal. However, the thresholds analysis provides general guidelines needed for the nitrogen management of this estuarine system.

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the Nauset Estuary. The threshold is 0.45 mg/L for WMO-27.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Town Cove - Inner	WMO-25	0.598	0.499	-30.9%
Town Cove - Inner	WMO-26	0.579	0.487	-30.8%
Town Cove - Inner	**WMO-27**	**0.527**	**0.451**	**-30.5%**
Town Cove - Outer	WMO-28	0.443	0.395	-29.7%
Town Cove - Outer	WMO-29	0.411	0.372	-29.3%
Nauset Marsh - South	WMO-30	0.356	0.334	-28.1%
Wood Cove	WMO-31	0.508	0.456	-22.7%
Nauset Marsh - South	WMO-32	0.331	0.317	-26.0%
Mill Pond - Outer	WMO-33	0.429	0.411	-12.0%
Mill Pond - Middle	WMO-34	0.507	0.491	-6.9%
Mill Pond - Inner	WMO-35	0.599	0.584	-4.7%
Nauset Marsh - North	WMO-36	0.412	0.383	-21.9%
Nauset Marsh - North	WMO-37	0.459	0.414	-24.9%
Salt Pond	WMO-38	0.618	0.504	-33.6%
Nauset Marsh - North	WMO-39	0.477	0.473	-2.3%
Nauset Marsh - North	WMO-40	0.325	0.319	-13.7%

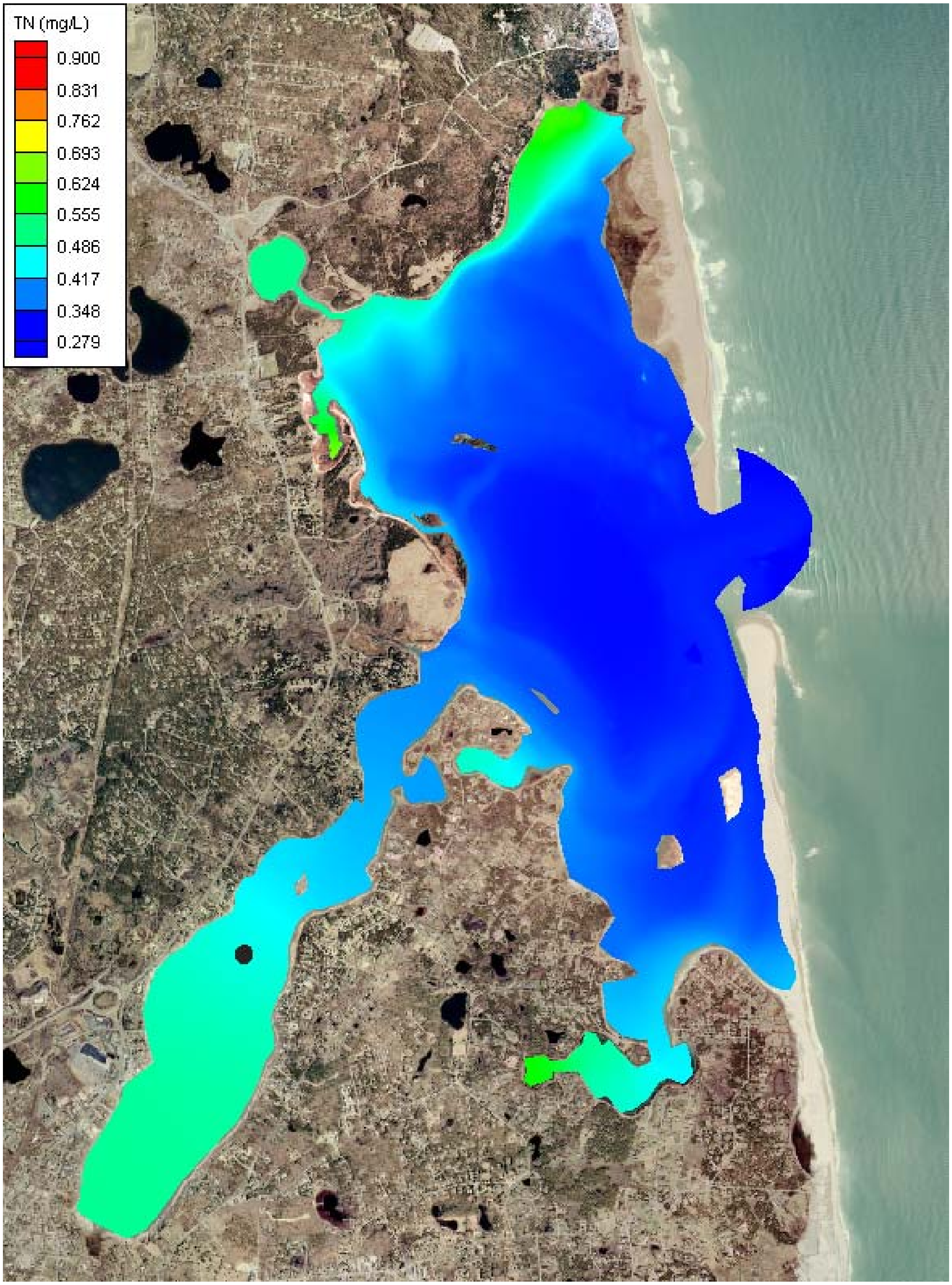


Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Nauset Estuary, for threshold conditions. The threshold station (WMO-27) has a target TN threshold of 0.45 mg L^{-1} in Town Cove (black dot) for eelgrass restoration, with TN levels below 0.50 mg L^{-1} for benthic infaunal habitat restoration for the overall system.

IX. REFERENCES

Applied Coastal Research and Engineering, Inc., Applied Science Associates, Inc., and School of Marine Science and Technology, University of Massachusetts at Dartmouth. 2001. Water Quality Analyses of Coastal Embayments in Chatham, MA. Mashpee, MA.

Aubrey Consulting, Incorporated, (1997). “Hydrodynamic and Tidal Flushing Study of Pleasant Bay Estuary, MA.” Report prepared by John S. Ramsey for the Pleasant Bay Steering Committee.

Aubrey, D.G., G. Voulgaris, W.D. Spencer, S.P. O’Malley (1997), Tidal Circulation and Flushing Characteristics of the Nauset Marsh System: Report to the Town of Orleans, WHOI.

Aubrey, D.G., W. Robertson V, (1998), Beach Changes and Management Options for Nauset Barrier Beach and Orleans Town Beach, Cape Cod, MA.: Report to the Town of Orleans, WHOI.

Bannon, Rebecca O., and Charles T. Roman. 2008. Using Stable Isotopes to Monitor Anthropogenic Nitrogen Inputs to Estuaries. Ecological Applications 18:22–30. [doi:10.1890/06-2006.1]

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.”

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

Campopiano, J. 2006. Operational Summary of the Wastewater Treatment System at the Salt Pond Visitors Center. Wickford, RI.

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, (1998). “Cape Cod Coastal Embayment Project.” Barnstable, MA.

Cape Cod Commission. 1998. *Pleasant Bay Nitrogen Loading Study, Final Report May 1998, Water Resources Office, Cape Cod Commission.*

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

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

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

Carmichael, R.H. and B. Annett and I. Valiela. 2004. Nitrogen loading to Pleasant Bay, Cape Cod: application of models and stable isotopes to detect incipient nutrient enrichment of estuaries. Marine Pollution Bulletin 48:137-143.

CDM. February, 2011. Town of Brewster, Massachusetts Integrated Water Resource Management Plan, Phase 1 – Needs Assessment. Final Report.

Chatham Water Quality Laboratory 2005. Chatham Coastal Water Quality Nutrient Monitoring Program: Year 5 Summary Report. R. Duncanson Director, 35 pp.

Colman, J.A., J.P. Masterson. 2008. Transient Simulations of Nitrogen for a Coastal Aquifer and Embayment, Cape Cod, MA., Environmental Science and Technology, 42, pp. 207-213.

Crusius, J., D. Koopmans, J.F. Bratton, M.A. Charette, K. Kroeger, P. Henderson, L. Ryckman, K. Halloran, J.A. Colman. 2005. Submarine Groundwater Discharge to a Small Estuary Estimated from Radon and Salinity Measurements and a Box Model, Biogeosciences, 2, pp. 141-157, 2005.

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.

DeSimone, L.A., P.K. Weiskel, B.L. Howes, and K.P. Smith. 1998. Water-Quality Data Collected in a Coastal Marsh, Orleans, Cape Cod, Massachusetts, March 1993 through January 1998. USGS Open-File Report 98-184. United States Geological Survey, Marlborough, MA.

Duncanson, R. (2000). Personal Communication. Water Quality Laboratory, Town of Chatham, MA

Duncanson, R., 2000. Memorandum dated March 20, 2000 to the Comprehensive Wastewater Management Plan TAC and CAC and to others describing the Town of Chatham's Coastal Water Nutrient Monitoring Program. 9 pp.

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

Earth Tech, Inc., (2002). Groundwater modeling in support of a comprehensive wastewater management plan, Chatham, MA. Technical Report to the Chatham Water Department, 90 pp.

Eichner, E. 2009. Eastham Freshwater Ponds: Water Quality Status and Recommendations for Future Activities. Coastal Systems Program, School of Marine Science and Technology, University of Massachusetts Dartmouth and Cape Cod Commission. New Bedford and Barnstable, MA. 155 pp.

Eichner, E.M. 2007. Review and Interpretation of Orleans Freshwater Ponds Volunteer Monitoring Data. Prepared for the Town of Orleans Marine and Fresh Water Quality Task Force and Barnstable County. Cape Cod Commission. Barnstable, MA.

Eichner, E.M. 2007. Review and Interpretation of Orleans Freshwater Ponds Volunteer Monitoring Data. *Final Draft.* Cape Cod Commission, Barnstable, MA. Completed for Town of Orleans Marine and Fresh Water Quality Task Force and Barnstable County.

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., K. Livingston, B. Smith, and V. Morrill. 1998. Pleasant Bay Nitrogen Loading Analysis. Cape Cod Commission, Water Resource Office. Barnstable, MA.

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, 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.

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

Fiegel, 2011. Statistical Analysis of Multi-year Water Quality Monitoring Data 2003-2010

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.

Geise, G.S. (1988). "Cyclical Behavior of the Tidal Inlet at Nauset Beach, Massachusetts: Application to Coastal Resource Management." In: Lecture Notes on Coastal and Estuarine Studies, Volume 29, Symposium on Hydrodynamics and Sediment Dynamics of Tidal Inlets (D. Aubrey and L. Weishar, eds.), Springer-Verlag, NY, pp. 269-283.

Guo, W., and Langevin, C.D., 2002, User's guide to SEAWAT: A computer program for simulation of three-dimensional variable-density ground-water flow: U.S. Geological Open-File Report 01-434, 77 p.

Harbaugh, A.W. and McDonald, M.G., 1996. User's Documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model: U.S. Geological Survey Open-File Report 96-485, 56p.

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

Heufelder, G., S. Rask, and C. Burt. Performance of Innovative Alternative Onsite Septic Systems for the Removal of Nitrogen in Barnstable County, Massachusetts 1999-2007. Barnstable County Department of Health and the Environment. Barnstable, MA.

Horne, G.S. and C.F. Horne. 2001. Reconnaissance Hydrography of the Upper Reaches of Little Pleasant Bay, Orleans MA.

Horsley Witten Group. 2009. Evaluation of Turfgrass Nitrogen Fertilizer Leaching Rates in Soils on Cape Cod, Massachusetts. Prepared for Brian Dudley, Department of Environmental Protection. Sandwich, MA.

Horsley Witten Hegemann, Inc. (1992). "Comprehensive Harbor Management Plan, Chatham, Massachusetts." Report prepared for the Chatham Harbor Planning Committee. 157 pp. + appendices.

Howes B., H.E. Ruthven, J. S. Ramsey, R. Samimy, D. Schlezinger, J. Wood, E. Eichner (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Centerville River System, Barnstable, 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., 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, E. Eichner (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Pleasant Bay, Chatham, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B.L., E.M. Eichner, S.W. Kelley, J. S. Ramsey, R.I. Samimy, D.R. Schlezinger (2007a). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Little Namskaket Marsh Estuarine System, Orleans, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B.L., S.W. Kelley, J.S. Ramsey, R.I. Samimy, D.R. Schlezinger, E.M. Eichner. 2007b. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Rock Harbor Embayment System, Orleans, Massachusetts. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B.L., S.W. Kelley, J.S. Ramsey, R.I. Samimy, E.M. Eichner, D.R. Schlezinger. 2007c. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Namskaket Marsh Estuarine System, Orleans, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes, B.L. and D.R. Schlezinger, 2000. Excel spreadsheet: summary tables of nutrient flux from 48 sediment cores collected from Chatham coastal embayments July 18-20, 2000. Coastal Systems Program, SMAST, Umass Dartmouth.

Howes, B.L. and J.S. Ramsey. 2002. Water Quality & Habitat Health of the Embayment Systems of Orleans, MA, Progress Report from the 2001 & 2002 Field Seasons:

Howes, B.L., D. White, R. Samimy. 2006. Cockle Cove Salt Marsh Nitrogen Threshold. Massachusetts Estuaries Project Technical Memorandum.

Johnson, D.G. and N.M. Davis. 1988. Water-Table Map of Brewster and Harwich, Massachusetts: September 21 to October 22, 1987. U.S. Geological Open-File Report 88-330, 1 plate.

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

Kelley, S.W., J.S. Ramsey, J.M. Côté, and Jon D. Wood, 2001. Tidal flushing analyses of coastal embayments in Chatham, MA. Applied Coastal Research and Engineering report to the Town of Chatham.

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

King, Ian P. (1996). "Users Guide to RMA2 Version 4.2." US Army Corps of Engineers – Waterways Experiment Station Hydraulics Laboratory.

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

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.

Leab, M.P., T.C. Cambareri, D.J. McCaffery, E.M. Eichner, and G. Belfit. 1995. Orleans Water Table Mapping Project, Orleans, Massachusetts. Completed for the Town of Orleans.

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

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.

Masterson, J.P. 2004. Simulated interaction between freshwater and saltwater and effects of ground-water pumping and sea-level change, Lower Cape Cod aquifer system, Massachusetts: U.S. Geological Survey Scientific Investigations Report 2004-5014, 72 pp.

Metcalf & Eddy. 1983. "Report to the United States Environmental Protection Agency on the Affordability of Sewers in the Town of Orleans, Massachusetts".

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

Millham, N.P. and B.L. Howes (1994b). Patterns of groundwater discharge to a shallow coastal embayment. 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.

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

National Park Service, Department of Interior, 1994.Groundwater Nutrient Concentrations Around Nauset Marsh. Final Report and Data Appendix A

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.

Nowicki, B.L., E. Requintina, D. Van Keuren, J. Portnoy. 1999. The Role of Sediment Denitrification in Reducing Groundwater-Derived Nitrate Inputs to Nauset Marsh Estuary, Cape Cod, Massachusetts. Estuaries, vol. 22, issue 2: pp. 245-259.

Oldale, R.N. 1992. Cape Cod and the islands—The Geologic Story. Parnassus Imprints, East Orleans, MA. 205 p.

Oldale, R.N., C. Koteff, and J.H. Hartshorn. 1971. Geologic Quadrangle Maps of the United States, Geologic Map of the Orleans Quadrangle, Barnstable County, Cape Cod, Massachusetts. US Geological Survey, Map GQ-931.

Pleasant Bay Citizen Water Quality Monitoring Program 2001. Quality Assurance Project Plan.

Pleasant Bay Citizen Water Quality Monitoring Program: 2000. Raw Data from the Orleans Marine Water Quality Task Force (1998-2000.)

Pleasant Bay Technical Advisory Committee, and Ridley & Associates, Inc., 1998. Pleasant Bay resource management plan. Report to the Pleasant Bay Steering Committee, 158 pp + appx.

Pollock, D.W., 1994. User's Guide to MODPATH/MODPATH_PLOT, version 3 – A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey modular three dimensional finite-difference ground-water-flow-model: U.S. Geological Survey Open-File Report 94-464, [variously paged]

Portnoy, J. W., B. L. Nowicki, C. T. Roman, and D. W. Urish (1998), The discharge of nitrate-contaminated groundwater from developed shoreline to marsh-fringed estuary, *Water Resour. Res.*, 34(11), 3095–3104, doi:10.1029/98WR02167.

Poucher, S. and L. Coiro. 1997. Test Reports: Effects of low dissolved oxygen on saltwater animals. Memorandum to D.C. Miller. U.S. Environmental Portection Agency, Atlantic Ecology Division, Narragansett, Rhode Island. (Cited in New York State Aquatic Fact Sheet on Ambient Water Quality Value for Protection of Aquatic Life, 2008).

Ramsey, J.S. 1997. Hydrodynamic and Tidal Flushing Study of Pleasant Bay Estuary, MA. Aubrey Consulting, Inc. Report.

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.

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.

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

Stearns and Wheeler, LLC. (1999). "Final Needs Assessment Report for Comprehensive Wastewater Management Planning Study." Report prepared for the Town of Chatham.

Stearns and Wheler, 2001. Summary of existing and future nitrogen loading (kg/yr), Pleasant Bay embayments in Chatham. Word document file communicated by R. Duncanson, Chatham Water Quality Laboratory.

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.

Town of Orleans. 1997. "Nutrient Monitoring of Orleans Salt Water Ponds of Pleasant Bay".

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

USGS 2007. Transient Simulations of Nitrogen Load for a Coastal Aquifer and Embayment, Cape Cod, MA.

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

Walter, D.A., and Whealan, A.T. 2005. Simulated Water Sources and Effects of Pumping on Surface and Ground Water, Sagamore and Monomoy Flow Lenses, Cape Cod, Massachusetts: U.S. Geological Survey Scientific Investigations Report 2004-5181, 85 p.

Water Quality Monitoring and Hydrodynamic Modeling. Technical Report to the Orleans Wastewater Management Steering Committee. Coastal Systems Program, School for Marine Science and Technology – University of Massachusetts Dartmouth, 76 pp

Weiskel, P.K., L.A. DeSimone, and B.L. Howes. 1996. A nitrogen-rich septage-effluent plume in a coastal aquifer, marsh, and creek system, Orleans, Massachusetts: project summary, 1988-95. USGS Open-File Report 96-111. United States Geological Survey, Marlborough, MA.

Wineman, R.J. 1997. *Orleans Marine Water Quality Task Force: Nutrient Project. Report to Town of Orleans.*

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.

Woods Hole Group, (1998). “Revised Flushing Calculations for Pleasant Bay Estuary.” Report revisions prepared for the Pleasant Bay Steering Committee.

Woods Hole Group, (1999c). “Re: Pleasant Bay/Ryder Cove Tidal Flushing Study.” Letter from Bob Hamilton to Dr. Robert Duncanson dated October 21, 1999.

Woods Hole Group, (1999d). “Results of updated Pleasant Bay Estuary flushing modeling.” Letter from Bob Hamilton to Dr. Robert Duncanson dated December 16, 1999.

Woods Hole Oceanographic Institution, November 1983. The Coastal Impact of Groundwater Discharge: an assessment of anthropogenic nitrogen loading in Town Cove, Orleans, MA.

Wright Pierce Inc. 2005. Tri-Town Septage Treatment Facility Evaluation. Report to the Wastewater Management Steering Committee Town of Orleans, MA. 146 pp.

Wright-Pierce, Teal Ltd, and CLF Ventures. 2004. Enhancing Wastewater Management on Cape Cod: Planning, Administrative and Legal Tools, Report to Barnstable County. Prepared for the Barnstable County Wastewater Implementation Committee.

Wright-Pierce. December, 2010. Town of Orleans, Comprehensive Wastewater Management Plan, Final Report. (http://town.orleans.ma.us/Pages/OrleansMA_BComm/cwmpfinal

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.