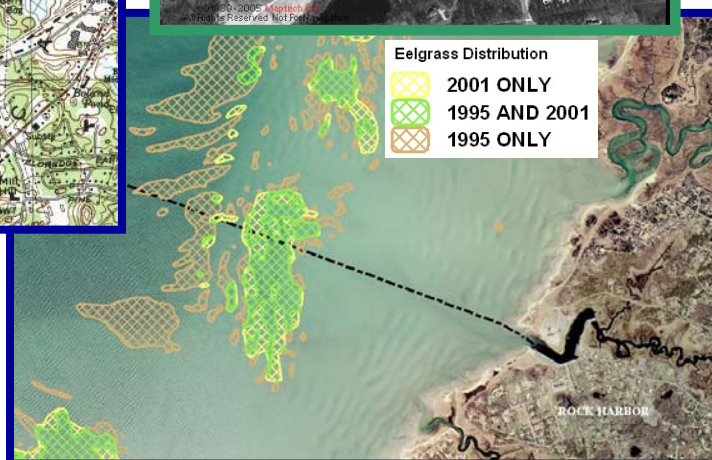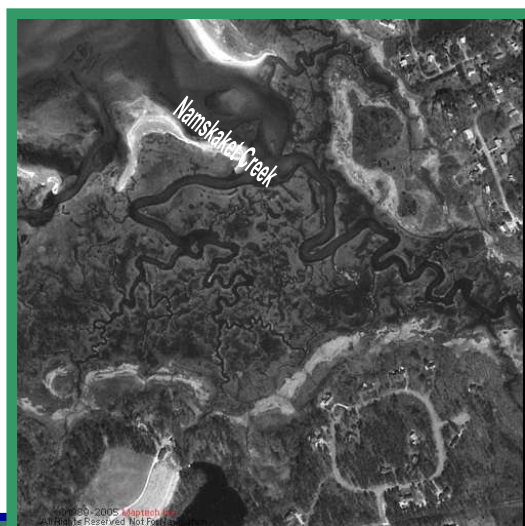# Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Namskaket Marsh Estuarine System, Orleans, MA

University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

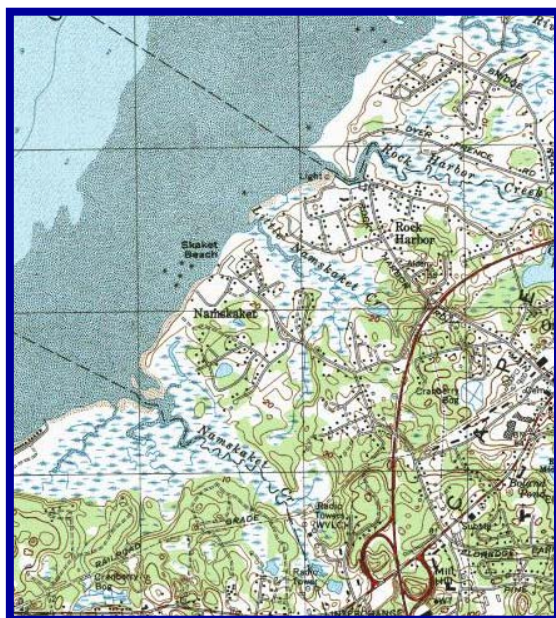*FINAL REPORT – December 2008*

Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Namskaket Marsh Estuarine System, Orleans, Massachusetts

FINAL REPORT – December 2008

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Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Namskaket Marsh Embayment System Town of Orleans, Massachusetts

Executive Summary

1. Background

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Namskaket Marsh embayment system, a coastal embayment situated within the Town of Orleans, Massachusetts. Analyses of the Namskaket Marsh embayment system was performed to assist the Town 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 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 Namskaket Marsh embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Town) for the restoration / protection of the Namskaket 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 Namskaket embayment system within the Town of Orleans (though primarily a large salt marsh environment) is at risk of eutrophication (over enrichment) in its upper reaches if enhanced nitrogen loads entering through groundwater and surface water from the increasingly developed watersheds to this complicated estuarine system eventually exceed the salt marshes ability 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 has 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) 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 (2008). 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 Namskaket Marsh 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 watershed boundaries were delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Namskaket Marsh 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 Namskaket Marsh embayment 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 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 streams discharging directly to the embayment. Boundary nutrient concentrations in the Cape Cod Bay source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Namskaket Marsh embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the embayments.

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

The 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 Namskaket Marsh 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 Namskaket Marsh 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 in the Namskaket Marsh watershed in order to effectively examine the effect of load increases/reductions on water column nutrient concentrations.

It is important to note that contrary to most other estuarine systems evaluated as part MEP, the threshold concentration for Namskaket Marsh (similar to the adjacent Little Namskaket Marsh) was set higher than present conditions, meaning that the system would be allowed to have a higher load than present while still being able to meet the threshold. Therefore, watershed nitrogen loads were sequentially raised in the model until the nitrogen levels reached the threshold level at the sentinel station (WMO-23) chosen for Namskaket Creek. It is important to note that load increases could be produced by increasing of any or all sources of nitrogen to the system. The load increases presented in this report represent only one of a suite of potential approaches that need to be evaluated by the community. The current presentation is to establish the general degree and spatial pattern of loading that will be allowable for this system.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout Namskaket Marsh system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. The Namskaket Estuary is showing high habitat quality throughout its salt marsh reach. The upper reach appears to be a fully functional tidal salt marsh with deeply incised narrow creeks surrounded by

extensive emergent marsh. This reach is typical of New England "pocket" marshes, with smaller tidal creeks and a marsh plain dominated by low marsh and high marsh plant communities with patches of fringing brackish marsh vegetation. The lower reach of the marsh supports a large wetland area to the west along with larger tidal creeks. The lower portion of the system is also heavily influenced by sand transport via nearshore coastal processes associated with adjacent Cape Cod Bay. Plant communities in the lower reach are similar to the upper reach except that there is less fringing brackish water species and the marsh grades to barrier beach/dune vegetation near the tidal inlet. All of the key habitat indicators are consistent within Namskaket Marsh, and particularly its tidal creeks, supporting high quality habitat in line with the system's salt marsh structure and function (Chapter VII).

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 Namskaket Marsh embayment system were comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 85% of the controllable watershed nitrogen load to the embayment was from wastewater.

As a salt marsh dominated estuary, Namskaket Marsh does not support eelgrass habitat. As a result, threshold development for protection/restoration of this system focuses on infaunal habitat quality. The primary mechanism for infaunal habitat quality decline in salt marsh creeks of this type is through stimulation of macroalgal production and accumulation.

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Namskaket 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:

Namskaket Marsh Threshold Nitrogen Concentrations

- Namskaket Marsh is presently below the level of nitrogen loading that would cause impairment to its infaunal habitats (i.e. below its nitrogen threshold level), therefore, a conservative estimate of the threshold was established. The threshold was based upon site-specific data and comparison to other similar systems on Cape Cod where detailed nitrogen threshold studies have been completed. The inter-estuarine comparison focused upon similar salt marshes which are presently experiencing higher nitrogen levels, with and without impairment.

- A principal component of the high tolerance of salt marsh systems to nitrogen inputs from groundwater and surface water inflows is that unlike embayments, creek waters cannot accumulate nutrients over multiple tidal cycles as embayments do. In addition, increasing the nitrogen concentration in the tidal waters that flood the marsh plain will have a negligible or possibly a stimulatory effect on marsh primary and likely secondary production (i.e. an enhancement of habitat). In addition, since the inflowing fresh waters flow down gradient through the marsh creek and out to the adjacent offshore waters, the nitrogen level will never exceed the inflowing freshwater nitrogen level.

- A detailed nitrogen threshold analysis of Cockle Cove Creek (Chatham), a similarly configured salt marsh to Namskaket Creek, has recently been completed (SMAST 2006). In addition to having similar structures, Cockle Cove Creek and Namskaket Creek both support similar benthic communities, macroalgal accumulations are sparse to absent in both systems and tidal velocities within the central creek are similar. In addition, the infaunal habitats within Namskaket and Cockle Cove Marsh are similar in composition and diversity (dominated by polychaetes and crustaceans, with some mollusks). The dominant species (*Leptocheirus, Paranais*) was also observed in a study of a healthy salt marsh, Great Sippewisset Marsh on Cape Cod.

- Putting all the assessment elements together, it appears that for Namskaket Creek, the critical values are a total nitrogen level of 2 mg N L^{-1} in the headwaters and a level of 1 mg N L^{-1} at the border of the upper and lower reach (Station WMO-23). As this upper/lower boundary station is the uppermost long-term marine water quality sampling site and integrates all of the watershed and upper marsh nitrogen inputs and removals, it was selected as the sentinel station for this system (WMO-23). The threshold (tidally averaged) total nitrogen level of 1 mg N L^{-1}.was determined to be appropriate for the sentinel station (WMO-23). It should be noted that the tidally averaged total nitrogen level at the middle marsh station in Cockle Cove Creek is currently 1.378 mg N L^{-1} and the tidal inlet station shows concentrations of 0.472 mg N L^{-1}, consistent with the 1 mg N L^{-1} at the sentinel station in Namskaket Marsh. This threshold applies as long as the tidal creek maintains its present hydrodynamic characteristics (flushing and velocity). The nitrogen threshold for Namskaket Marsh is intentionally conservative based upon all available data from comparable systems. However, it indicates that additional nitrogen may enter this system without impairment of its habitat quality throughout the estuary.

- As presented in Chapter VIII, the threshold set for this system would allow up to 3.6 times (261% increase) the present watershed loading. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

The overarching conclusion of the MEP analysis of the Namskaket Marsh estuarine system is that protection of this currently healthy salt marsh system will allow for increased nitrogen loading from a variety of watershed sources, however, limits to nitrogen loading have been determined as detailed further in the report. This requires careful long term monitoring of conditions in the marsh system and watershed based management of present and future nitrogen inputs such that nitrogen concentration thresholds specified as supportive of health marsh habitat are not exceeded in the future.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Namskaket Marsh system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Namskaket system include both upper watershed regions contributing to the major surface water inputs.										

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
NAMSKATET MARSH SYSTEM										
Namskaket marsh	5.334	3.346	5.944	3.245	9.29	0.118	-0.409	8.999	0.52-0.84	--
Namskaket Creek (freshwater)	0.8	1.306	2.088	-	3.395	-	-	3.395	1.21	--
Namskatet Marsh System Total	6.134	4.652	8.032	-	12.685	0.118	-0.409	12.394	**0.52-1.21**	**1.000**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing unattenuated wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings
[5] atmospheric deposition to embayment surface only.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of data collected between 2001 and 2006, ranges show the upper to lower regions (highest-lowest) of the indicated sub-embayment.
[8] threshold for sentinel site located at mid-point WQ monitoring station of the system.

Table ES-2.	Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Namskaket 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 change in watershed load to achieve allowed threshold load levels
NAMSKATET MARSH SYSTEM						
Namskaket marsh	9.29	31.510	0.118	-0.317	31.628	+239.2%
Namskaket Creek (freshwater)	3.395	14.381	-	-	14.381	+323.6%
Namskatet Marsh System Total	12.685	45.890	0.118	-0.317	46.008	+261.8%

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

ACKNOWLEDGMENTS

CITATION

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I. INTRODUCTION

Namskaket Marsh is an 80 hectare (200 acre) salt marsh on the northeastern coast of Cape Cod, with adjacent similar systems of Rock Harbor and Little Namskaket Marsh. These three salt marsh systems are located within the Towns of Orleans, Eastham and Brewster on Cape Cod Massachusetts. All three of these systems are situated on the north shore of Cape Cod and are tidal salt marshes receiving tidal flood water from Cape Cod Bay (Figure I-1). Though all three systems are typical salt marshes, the Rock Harbor system has been significantly modified to create a harbor just inside the inlet. The harbor area encompasses the lower quarter of the main tidal creek and supports a small marina and docks for private and commercial fishing vessels. Both Namskaket Marsh and Little Namskaket Marsh have small, deeper water areas immediately inside their inlets to Cape Cod Bay. However, in both of these systems these regions are "natural" and do not retain significant water volume at low tide. Each of these three estuarine systems is predominantly tidal salt marsh with a central tidal creek and smaller tributary tidal creeks.   Only Rock Harbor, exhibits "open water" embayment characteristics, associated with the dredged harbor basin. The watersheds contributing nitrogen to the waters of the Rock Harbor, Little Namskaket Marsh and Namskaket Marsh systems are distributed among the Towns of Orleans and Eastham, Orleans and Orleans and Brewster, respectively. Restoration of any degraded habitats within these estuarine salt marsh systems will depend upon the coordinated efforts of these municipalities and their citizens.

Overall, the Namskaket Marsh system is a typical New England salt marsh dominated by a central tidal creek and emergent marsh colonized by low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) with some more brackish marsh plants found in the upper most regions and limited bordering patches of *Phragmites*. Tidal exchange with the high quality waters of Cape Cod Bay is high, given the ca. 10 foot tide, which has also resulted in tidal creeks which are deeply incised, with near complete drainage at low tide. The result is the type of coastal system which has a relatively high tolerance for nitrogen inputs from its watershed. Observations by the USGS and the MEP Technical Team indicate a healthy functioning New England Salt Marsh.

Namskaket Marsh provides both wildlife habitat and a nursery to offshore fisheries, as well as serving as a storm buffer and nutrient sink for watershed derived nitrogen.   The upper upland margin of Namskaket Marsh currently supports a bicycle trail that is frequented by many local citizens and visitors each year. As recognition of its natural beauty and critical value to regional environmental quality, Namskaket Marsh has been designated as an Area of Critical Environmental Concern and an Outstanding Resource Water by the Commonwealth of Massachusetts [Massachusetts General Law, chapter 21a, sections 2(7) and 40(e)].

Namskaket Marsh is a small estuary behind a barrier beach formed by coastal processes associated with nearshore Cape Cod Bay. This estuarine system is a relatively "young" 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. At present, streams are relatively small and discharge only a small portion of the aquifer recharge to the estuary. Streams are not well formed, with almost all freshwater entering through groundwater seepage either to the restricted wetlands at the head of the salt marsh (Hurleys Bog or Inner Namskaket Marsh (near the Radio Tower) or directly through marginal and creek bottom seepage.
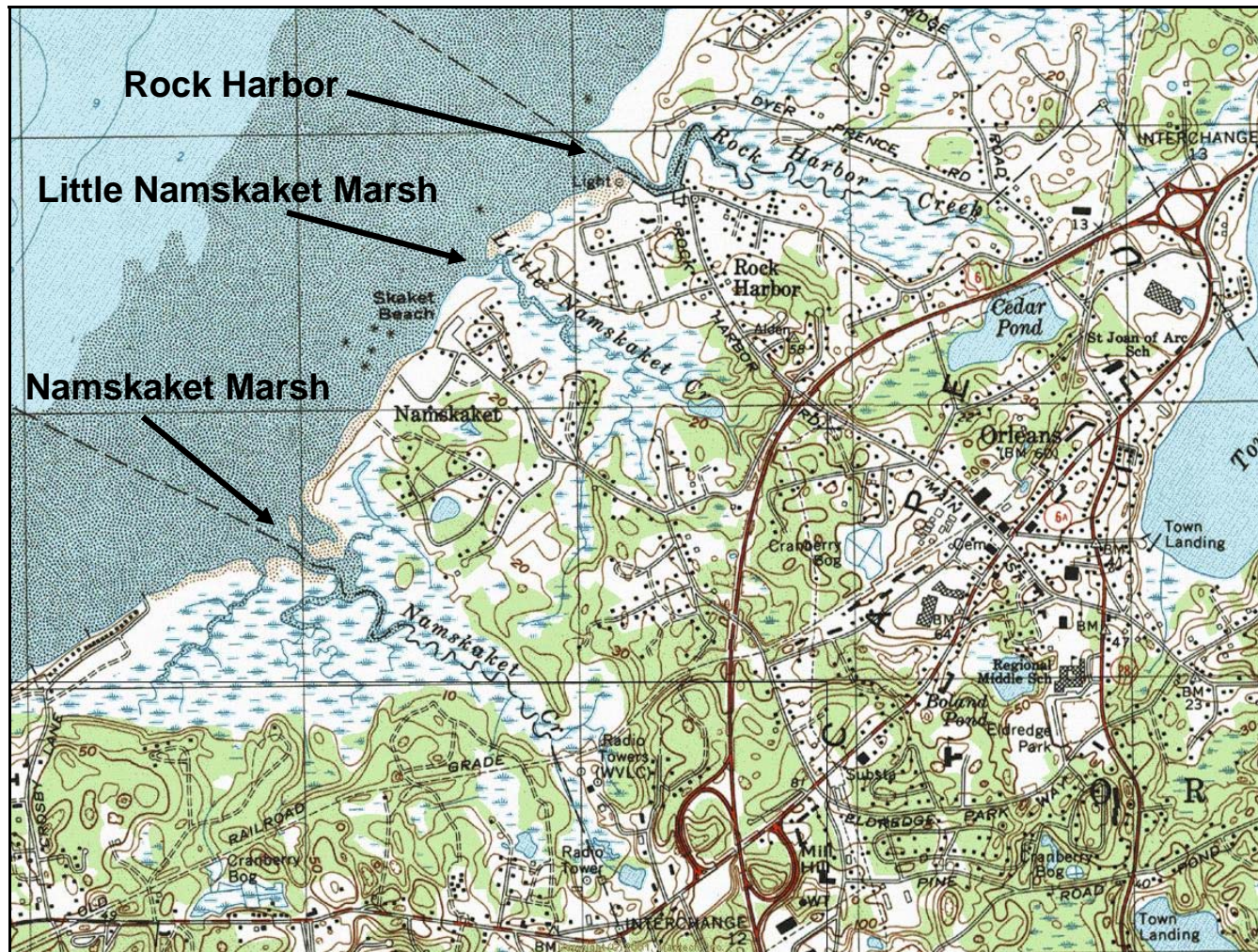
Figure I-1.   Study region for the Massachusetts Estuaries Project nitrogen thresholds analysis for Rock Harbor, Little Namskaket Marsh and Namskaket Marsh. Tidal waters enter the system through one inlet in each of the three systems. Flood waters enter the systems from Cape Cod Bay. Freshwaters enters the head of each system from the watershed primarily through 1 surface water discharge point in each marsh, as well as direct groundwater discharge.

Tidal exchange with Cape Cod Bay is through a 430-foot wide main inlet, and a 200-foot-wide secondary inlet, both which empty onto a broad tidal flat over Skaket Beach. The beach and the inlet are very dynamic geomorphic features, due to the influence of littoral transport processes. These processes may periodically affect the health of this estuary through changes in hydrodynamics wrought by inlet dynamics (see Chapter V). To the extent that the inlet becomes restricted and tidal flushing is reduced, nitrogen loading impacts will be magnified over present conditions. Equally important, to the extent that tide range may become reduced, the health and productivity of the emergent salt marsh would be reduced. Any long term habitat management plan for the Namskaket Marsh System must recognize the importance of inlet dynamics and include options to maintain tidal exchange.

The primary ecological threat to Namskaket Marsh resources is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen has been increasing over the past few decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to this and other outer Cape estuaries (such as Nauset in the Town of Orleans), like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater or disposal of treated effluent from municipal treatment facilities. The Town of Orleans has been among the fastest growing towns in the Commonwealth over the past two decades and does not have centralized wastewater treatment, although it is associated with the Tri-Town Septage Treatment Facility, located in the upper Namskaket Marsh watershed. As levels of nitrogen loading to coastal systems continue to increase, concern has grown in outer Cape Cod Towns over associated nutrient impacts.

Fortunately for the resource protection of Namskaket Marsh, its function as a tidal salt marsh makes it more tolerant of watershed nitrogen inputs than coastal embayments, like nearby Town Cove or Pleasant Bay. The greater sensitivity of embayments versus wetlands results from their lower tidal exchange rates, the fact that there is limited to no exposure of the sediments to the atmosphere at low tide (like the marsh plain), and the fact that these systems have evolved under much lower levels of productivity and organic matter loading than wetlands. For example, the organic carbon content of New England Salt Marsh vegetated sediments can frequently reach 20%, while embayment sediments are generally in the 1%-5% range. Yet another difference between system types is that oxygen depletion in the creeks of *pristine* wetlands can normally occur on summer nights, while embayment bottom waters become hypoxic generally as a result of *eutrophic* conditions.

Some additional insight into the nitrogen response by salt marshes can be garnered from long-term chronic nitrogen addition experiments. These have been conducted at multiple sites along the Atlantic coast and specifically in a nearby New England salt marsh, Great Sippewissett Marsh (West Falmouth, MA). This latter project was started by WHOI scientists in 1970 and has been overseen solely by current SMAST Staff since 1985. These studies reveal that nitrogen additions to low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) areas, typically results in increased plant production and biomass and secondary production as well. Nitrogen dynamics have been quantified, which show that as nitrogen is added the initial increased nitrogen available is taken up by the plants, but this plant demand is rapidly satisfied and additional load is denitrified *in situ* by soil bacteria. In the Great Sippewissett Marsh fertilization experiments the denitrification capacity of the sediments has not been exhausted in 30 years of N additions and at levels about 7 times the natural background N input (75.6 g N m^{-2} each growing season).

Salt marsh creek bottoms and creek banks (such as those found in Namskaket Marsh, Little Namskaket Marsh and the Rock Harbor marsh areas) have developed under nutrient and

organic matter rich conditions, as have the organisms that they support. It is the creek bottoms rather than the emergent marsh which are the primary receptors of increased watershed derived nitrogen in Cape Cod salt marshes. Watershed nitrogen predominantly enters these salt marshes through groundwater or small headwater streams, as is the case in all three systems. Both surface and groundwater entry focuses on the tidal channels. Even groundwater entry through seepage at the upland interface is channeled to creek bottoms. As the tide ebbs in these New England salt marshes (like Little Namskaket and Namskaket Creek) the freshwater inflow "freshens" the waters and the nitrogen levels in the tidal creeks increase due to the nitrogen entry from the watershed. At low tide the nitrogen levels in the tidal creeks are dominated by watershed inputs.

Since the predominant form of nitrogen entering from the watershed is inorganic nitrate, the effect on the creek bottom is to stimulate denitrification, hence nitrogen removal. For example, in a salt marsh in West Falmouth Harbor, Mashapaquit Creek, ~40% of the entering watershed nitrogen is denitrified by the creek bottom sediments on an annual basis. This stimulation of denitrification does not negatively affect the salt marsh, but does result in a reduction of nitrogen loading to the adjacent nitrogen sensitive coastal waters. However, analysis by MEP Staff of salt marsh areas receiving wastewater discharges indicates that at very high nitrogen loads (inputs relative to tidal flushing), macroalgal accumulations can occur. These accumulations are generally found in the creek bottoms and flats and also may drift and settle on the creek banks. Large macroalgal accumulations in tidal creeks can cause impairment of benthic animal communities. In the latter case, negative effects on creek bank grasses can occur, which may lead to bank erosion and negative effects on organisms. A part of the focus of the present MEP analysis of the Namskaket Marsh System, relates to potential macroalgal issues.

The Towns of Orleans and Brewster are the primary stakeholders to the Namskaket Marsh Estuary, the focus of this report. The Town of Orleans was among the first communities to become concerned over the existing and potential future degradation of its estuaries. As such, the Town of Orleans (via the Planning Office) undertook a town-wide monitoring effort, inclusive of Namskaket Marsh. The comprehensive water quality monitoring program was developed to acquire the necessary background water quality monitoring data from all the embayment systems in the Town of Orleans such that the MEP Linked Watershed-Embayment Management Modeling Approach could be applied to the development of nutrient thresholds. Moreover, water quality data generated by the Town of Orleans Water Quality Monitoring Program is consistent with that generated by the Town of Harwich and Chatham as well as the Pleasant Bay Alliance making the data for all the systems in this area cross comparable.

The common focus of the water quality monitoring efforts undertaken by the Towns of Orleans has been to gather site-specific data on the current nitrogen related water quality throughout the Rock Harbor, Namskaket Marsh and Little Namskaket Marsh systems as well as, Nauset Marsh and portions of Pleasant Bay as they exist within the Town of Orleans. These data were then utilized to 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 Orleans Water Quality Monitoring Program form a baseline from which to gauge long-term changes as watershed nitrogen management moves forward. This data has already proven to be of high quality and adequate for the development of management thresholds for each of the Town's coastal systems, as was demonstrated in the MEP nitrogen threshold analysis completed for the Pleasant Bay System (Howes et al. 2006).

The Orleans Water Quality Monitoring Program efforts allowed the MEP to prioritize all of the Orleans systems for the next step in the restoration/protection and management process.

The MEP effort builds upon the efforts of the water quality monitoring program, and previous hydrologic and water quality analyses undertaken by the US Geological Survey (as in Namskaket Marsh), and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Rock Harbor, Namskaket and Little Namskaket marsh systems.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning and nitrogen management alternatives development needed by the Town of Orleans for restoration of the its impaired embayment habitats. While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for the Town of Orleans to develop and evaluate the most cost effective nitrogen management alternatives to restore those valuable coastal resources of Orleans that have been 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 a watershed becomes 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, Harwich and Chatham) 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.

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 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment model available to address future regulatory needs.

The core of the Massachusetts Estuaries Project analytical method is the Linked Watershed-Embayment Management Modeling Approach. This approach represents the "next generation" of nitrogen management strategies. It fully links watershed inputs with embayment circulation and nitrogen characteristics. The Linked Model builds on and refines well accepted basic watershed nitrogen loading approaches such as those used in the Buzzards Bay Project, the CCC models, and other relevant models. However, the Linked Model differs from other nitrogen management models in that it:

- requires site specific measurements within each watershed and embayment;
- uses realistic "best-estimates" of nitrogen loads from each land-use (as opposed to loads with built-in "safety factors" like Title 5 design loads);
- spatially distributes the watershed nitrogen loading to the embayment;

- accounts for nitrogen attenuation during transport to the embayment;
- includes a 2D or 3D embayment circulation model depending on embayment structure;
- accounts for basin structure, tidal variations, and dispersion within the embayment;
- includes nitrogen regenerated within the embayment;
- is validated by both independent hydrodynamic, nitrogen concentration, and ecological data;
- is calibrated and validated with field data prior to generation of "what if" scenarios.

The Linked Model has been applied for watershed nitrogen management in ca. 30 embayments throughout Southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach's greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options.

The Linked Watershed-Embayment Model when properly parameterized, calibrated and validated for a given embayment becomes a nitrogen management planning tool, which fully supports TMDL analysis. The Model suggests "solutions" for the protection or restoration of nutrient related water quality and allows testing of "what if" management scenarios to support evaluation of resulting water quality impact versus cost (i.e., "biggest ecological bang for the buck"). In addition, once a model is fully functional it can be "kept alive" and corrected for continuing changes in land-use or embayment characteristics (at minimal cost). In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries.

Linked Watershed-Embayment Model Overview: The Model provides a quantitative approach for determining an embayment's: (1) nitrogen sensitivity, (2) nitrogen threshold loading levels (TMDL) and (3) response to changes in loading rate. The approach is fully field validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-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

Nitrogen Thresholds Analysis

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┌─────────────────┐   ┌─────────────────┐   ┌─────────────────┐
│     Tide,       │   │ Benthic Flux and│   │   Watershed     │
│ Bathymetry, and │   │  Water Column   │   │ Delineation &   │
│    Current      │   │  Measurements   │   │    N Load       │
│  Measurements   │   │   Section IV    │   │ Section III and │
│                 │   │                 │   │       IV        │
└─────────────────┘   └─────────────────┘   └─────────────────┘

┌─────────────────┐                        ┌─────────────────┐
│  Hydrodynamic   │                        │ Total Nitrogen  │
│    Modeling     │ ─────────────────────▶ │    Modeling     │
│   Section V     │                        │   Section VI    │
└─────────────────┘                        └─────────────────┘

          ┌─────────────────┐
          │ D.O., Eelgrass  │
          │ Infauna Surveys │
          │   Section VII   │
          └─────────────────┘

                                           ┌─────────────────┐
                                           │   Thresholds    │
                                           │  Development    │
                                           │   Section IX    │
                                           └─────────────────┘
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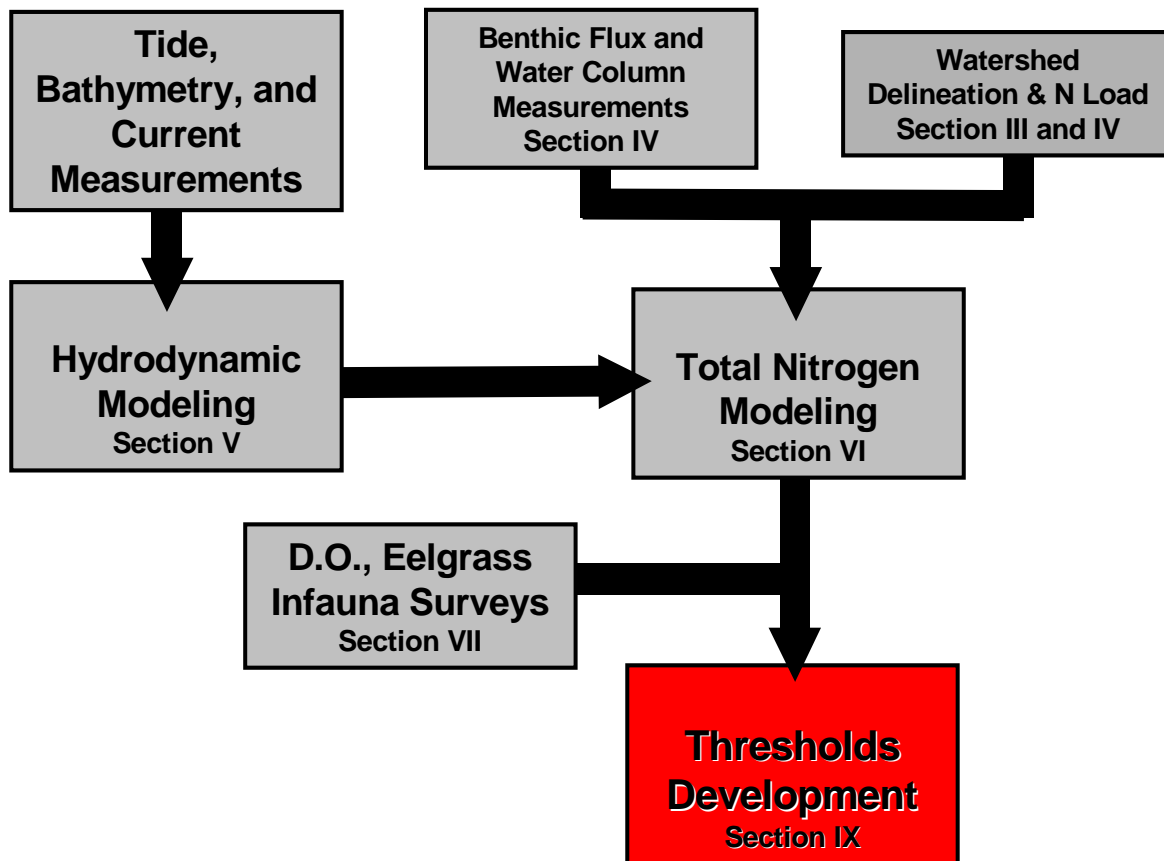
Figure I-2.   Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach.

I.2 SITE DESCRIPTION

The three Cape Cod Bay estuaries, associated with the Town of Orleans along with Brewster and Eastham (Rock Harbor, Namskaket Creek and Little Namskaket Creek), are among the larger of the coastal salt marsh systems of Cape Cod. As such, these systems are comprised of ca. 500 acres of barrier beach, salt marsh, and tidal flat. These three systems are situated on the northern shore of Cape Cod and each exchanges tidal waters with Cape Cod Bay through a single tidal inlet. The inlets can be significantly affected by longshore sand transport (west to east), where shoaling can impede hydrodynamic exchange at the mouth of each system and, in the case of extreme events, close an existing inlet and open a new one. The existing inlets to the Namskaket Marsh and Little Namskaket Marsh systems are natural inlets and are not armored in any way. In contrast, the inlet to Rock Harbor is armored and a navigational channel is maintained, however, shoals are abundant in the vicinity of the inlet and depths vary significantly. Depths throughout these three systems vary due to their tidal salt marsh characteristics in combination with the large tidal range in Cape Cod Bay. At low tide large areas of these marshes become nearly dry tidal creeks with large exposed tidal flats with little to no water at the mouths of these systems.

Namskaket Marsh occupies a triangular indentation in the coast sheltered by barrier dunes and beach sands (Oldale et al. 1971). The present configuration of the Namskaket Marsh Salt Marsh System results from a combination of glacially dominated geologic processes including the deposition of glacial outwash deposits and tidal flooding of post-glacial valleys formed primarily by post-glacial surface water erosion of the outwash. This estuarine system is a relatively "young" 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. Tidal exchange with Cape Cod Bay is through a single inlet through the barrier beach. The beach and the inlet are very dynamic geomorphic features, due to the influence of littoral transport processes. These processes may periodically affect the health of this estuary through changes in hydrodynamics driven by inlet dynamics (see Chapter V). To the extent that the inlet becomes restricted and tidal flushing is reduced, nitrogen loading impacts will be magnified over present conditions. Equally important, to the extent that tide range may become reduced, the health and productivity of the emergent salt marsh would be reduced. Any long term habitat management plan for the Namskaket Marsh System must recognize the importance of inlet dynamics and include options to maintain tidal exchange.

Similar to the larger adjacent Nauset marshes, Namskaket Marsh is a shallow coastal estuary dominated by salt marsh and tidal flats, as well as being located within a watershed that includes glacial outwash plain (Harwich Outwash Plain) and ice contact deposits (Nauset Height ice-contact deposits). These subsurface formations consist of material deposited after the retreat of the Laurentide Ice sheet ~15,000 years ago. These deposits, which form the present aquifer soils, are highly permeable and vary in composition from well sorted medium sands to course pebble sands and gravels (Oldale, 1992). As such, direct rainwater run-off is typically rather low and most freshwater inflow to these estuarine systems is via groundwater discharge or groundwater fed surface water flow. In the Namskaket Salt Marsh System almost all freshwater enters through groundwater seepage either to the restricted wetlands at the head of the salt marsh (Hurleys Bog or Radio Tower Bog) or directly through marginal and creek bottom seepage.

Namskaket Marsh acts as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Cape Cod Bay. Salinity levels vary with the volume of freshwater inflow as well as the effectiveness of tidal exchange. Given the large tidal flows and volumetric exchange, there is presently only minor dilution of salinity throughout most of the estuary at high tide. However, the system is a salt marsh, and as such, the elevation of the tidal creek bottoms is generally higher than the low tide elevation in the adjacent Bay (e.g. the creeks drain nearly completely at low tide). The result is that at low tide, the salinity of the out flowing Namskaket creek water is fresh to brackish, due to the dominance of the freshwater inflow in the absence of the tidal waters. As a result salinity variations of the creek waters in the upper marsh are very large with the range decreasing moderately toward the tidal inlet. Organisms associated with these creeks have developed strategies for dealing with these large salinity variations.

The Namskaket Marsh Estuary is a typical New England salt marsh dominated by a central tidal creek and emergent marsh colonized by low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) with some more brackish marsh plants found in the upper most regions and limited bordering patches of *Phragmites*. Tidal exchange with the high quality waters of Cape Cod Bay is high, given the ca. 10 foot tide, which has also resulted in tidal creeks which are deeply incised, with near complete drainage at low tide. The result is the type of coastal system which has a relatively high tolerance for nitrogen inputs from its watershed.

Overall, Namskaket Marsh appears presently to be a healthy functioning New England salt marsh as noted by USGS studies (DeSimone et al. 1998) and more recently during the MEP Technical Team's field survey. Nitrogen levels within the tidal creeks do show evidence of impairing the resource. However, the primary ecological concern relative to loss of Namskaket Marsh resources is degradation resulting from nutrient enrichment (and possibly restriction of tidal flushing due to coastal processes). Loading of the nitrogen has been increasing over the past few decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to this and other outer Cape estuaries, like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater or disposal of treated effluent from municipal treatment facilities. The Town of Orleans has been among the fastest growing towns in the Commonwealth over the past two decades and does not have centralized wastewater treatment, although it is associated with the Tri-Town Septage Treatment Facility, located in the upper Namskaket Marsh watershed. As levels of nitrogen loading to coastal systems continue to increase, concern has grown in outer Cape Cod Towns over associated nutrient impacts. However, as noted above, salt marshes are relatively insensitive to degradation by nitrogen inputs from the surrounding watershed. This results from the structure of the salt marsh within the upland hydrologic system and the natural nitrogen processing by these systems. In addition, the plants and animals within salt marshes have adapted to the high organic matter levels within the marsh sediments and associated waters and the associated biogeochemical effects. Critical to the MEP analysis of this salt marsh system is partitioning of salt marsh and embayment (basins retaining significant tidal volume at low tide, i.e. Town Cove) receptors.

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 watersheds to the Rock Harbor, Namskaket and Little Namskaket Marsh embayment systems, 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).

Nutrient related water quality decline represents one of the most serious threats to the ecological health of 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 marsh systems monitored by the Town of Orleans Water Quality Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) to "tune" general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important "boundary conditions" for water quality modeling of the three Orleans marsh systems; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within the systems. Therefore, water quality modeling of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. The spread of pollutants may be analyzed from tidal current information developed by the numerical models.

The MEP water quality evaluation examined the potential impacts of nitrogen loading into the marshes and all of the component tidal tributaries. 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 systems were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations by USGS using a modification of the Monomoy model for sub-watershed areas designated by MEP. Almost all nitrogen entering the marsh systems is

transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Cape Cod Bay source waters and the marsh systems themselves was taken from the water quality monitoring program run by the Towns of Orleans (associated with the Coastal Systems Program at SMAST). Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of these marsh systems 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 Namskaket Marsh Estuary in the Town of Orleans. A review of existing studies related to habitat health or nutrient related water quality is provided in Chapter II with a more detailed review of prior hydrodynamic investigations in Chapter 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 Chapters 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 (Chapter IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission data and offshore water column nitrogen values were derived from an analysis of monitoring station data on the flooding tide just inside the inlets to the marsh systems (Chapter IV). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Chapter VI. Results of hydrodynamic modeling of embayment circulation are discussed in Chapter 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 Chapter 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 (Chapter VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment in Chapter 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. This latter assessment represents only one of many solutions and is produced to assist the Town in developing a variety of alternative nitrogen management options for the marsh systems. Finally, analyses of the marshes was relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of dredging options to improve nitrogen related water quality.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

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

These tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. The present Massachusetts Estuaries Project (MEP) study focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species. The linked watershed-embayment model is built using estuarine specific measurements, thus enabling calibration of the prediction process for specific conditions in each of the coastal embayments and salt marshes of southeastern Massachusetts and Cape Cod, including the Namskaket Marsh, Little Namskaket Marsh and the Rock Harbor System (each being a combination of embayment in the lower portions and marsh in the upper reaches). 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.

Given the structural, ecological, hydrologic and hydrodynamic similarities of the Namskaket Marsh, Little Namskaket Marsh and the Rock Harbor Systems, previous studies related to one system generally were found to provide useful information for the modeling and assessment of the other two. For example, nitrogen levels in flooding waters to Rock Harbor provides a boundary condition to Namskaket and Little Namskaket Marshes as they share common offshore waters. The comparability of the salt marsh regions of these three systems led the MEP Technical Team to evaluate the numerous studies completed over the past two

decades as these were related to the nutrient related health of these estuaries. These investigations include both habitat assessments and studies relating to nitrogen loading, hydrodynamics and habitat health. While none of the previous studies provided a holistic view of even an individual system, they provide useful information to the present MEP effort.

The earlier efforts were generally survey studies to evaluate specific estuaries and their watersheds within the larger regional system, to assess the potential for specific watershed nitrogen sources to produce habitat declines within the receiving estuary, or focused studies of processes related to nitrogen cycling within the watershed and down gradient estuarine system. Given the need for diverse data sets to implement the Linked Management Approach, it was important to integrate all available information.

As part of the initial MEP process, the Orleans Wastewater Management Steering Committee and the Program Technical Team compiled more than 25 studies relating to the marine systems of Orleans. Of these 10 were selected as likely to contribute information or quantitative data to the Linked Management Approach. These studies were reviewed in 2001 by Project technical experts (all of whom are currently members of the MEP Technical Team) for (a) information or quantitative data to support the Linked Management Approach, (b) acceptability of results based upon quality assurance or comparability, and (c) data gaps seen in the integrated data set of the existing studies and present Program. Though these studies are related to other embayment systems, such as Nauset Marsh and Pleasant Bay, some information was potentially useful to the current MEP effort. In addition, there are a number of investigations, conducted by the USGS specifically related to nitrogen sources and inputs to Namskaket Marsh. A brief summary of the evaluations of the most pertinent studies is given below.

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

Project Summary: A yearlong 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 sewage 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 nitrogen and phosphorus are not limiting the phytoplankton and algal growth within Town Cove; 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.

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

Project Summary: The report describes the methods and results of the first phase of the study - 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 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 this 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 in #3, below. 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 with developed uplands.

(3) 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 22:245-259.

Project Summary: 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 in #2 above, to represent a range of nitrate levels and sediment types at the groundwater discharge sites.

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.

(4) Namskaket Marsh Studies Relating to Discharge of Treated Septage, by USGS and SMAST scientists (1998).

Project Summary: A large study has been on going within the upper watershed and salt marsh of Namskaket Creek. This investigation has resulted in numerous publications and technical reports. The focus of the study was to determine (a) the fate of nitrogen discharged to the aquifer from the Tri-Town Septage Treatment Facility, (b) predict potential effects on the Namskaket Marsh if the effluent nitrogen is discharged via groundwater, and (c) determine the timing and location of nitrogen discharge in groundwater.

Key findings related to the treated effluent plume from the Tri-Town Septage Treatment Facility located adjacent Namskaket Marsh stem from a number of USGS open file reports and journal articles. The basic results were:

- Assessment of the nitrogen mass to be discharged to the Cape Cod Bay Systems was quantified, but the discharge has still not reached the estuaries;
- the nitrogen plume is not being significantly attenuated during aquifer transport;
- the plume transport direction is sensitive to local recharge rates
- denitrification within the creek bottom sediments of Namskaket Marsh is large relative to the amount of nitrogen loading from the surrounding watershed and will increase if nitrate levels increase in entering freshwater
- groundwater does not enter the marsh through the marsh plain, but through a narrow seepage face at the upland/marsh boundary and through the creek bottoms.

In addition, the ability of the Namskaket Marsh to tolerate nitrogen inputs was evaluated. Nitrogen additions to both the vegetated marsh surface and creek bottoms were found to result in increased nitrogen loss through denitrification in the creek bottoms and increased production of the emergent marsh plants on the marsh plain.

These studies provide the information on the nitrogen tolerance of the salt marsh regions within the Cape Cod Bay Systems needed for the current nitrogen management program. These data will be incorporated into the present program.

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 (2007). 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 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.

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.

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 MODFLOW and MODPATH models 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 Namskaket Creek in the Towns of Orleans and Brewster. This estuary is situated along the northern edge of Cape Cod and is bounded by Cape Cod Bay.

In the present investigation, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the Namskaket Creek estuary system under evaluation by the Project Team. Further modeling of the estuary watersheds was undertaken to sub-divide the overall watersheds into functional sub-units based upon: (a) defining inputs from contributing areas to each major portion within the embayment system, (b) defining contributing areas to major freshwater aquatic systems which generally attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands), and (c) defining 10 year time-of-travel distributions within each sub-watershed as a procedural check to gauge the potential mass of nitrogen from "new" development, which has not yet reached the receiving estuarine waters. The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in the overall Monomoy groundwater flow cell. Model assumptions for calibration were matched to surface water inputs and flows from current (2002 to 2004) stream gage 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 the stream and the portion of the groundwater system that discharges directly into the estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Namskaket Creek estuary system and Flax Pond were delineated using a regional model of the Monomoy Lens flow cell (Walter and Whealan, 2005). The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, *et al.*, 2000) was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4 (Pollock, 2000), which uses output files from MODFLOW-2000 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

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water bodies. This approach was used to determine the contributing areas to the Namskaket Creek system and also to determine portions of recharged water that may flow through ponds and streams prior to discharging into coastal water bodies.

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. 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). The rewetting capabilities of MODFLOW-2000, which allows drying and rewetting of model cells, was used to simulate the top of the water table, which varies in elevation depending on the location in the Lens. Since water elevations are less than +40 ft in the portion of the Monomoy Lens in which the Namskaket Creek estuary resides, the three uppermost layers of the model are inactive.

The glacial sediments that comprise the aquifer of the Monomoy Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The sediments 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. The Namskaket Creek estuary watershed extends over a number of geologic settings. The northern portion near Flax Pond is generally located in the Harwich Plains, which were deposited as glacial ice lobes were retreating to positions near the current Cape Cod Bay shoreline and the barrier beach along the eastern edge of Pleasant Bay. These deposits are generally composed of sand and gravel (Oldale, *et al.*, 1971). The portions of the watershed closer to Cape Cod Bay are composed of Lake and Lake Bottom Deposits from the proglacial lake that once occupied Cape Cod Bay and are generally composed of clays and silts mixed with some sand. On top of these materials are the marsh and swamp deposits that generally surround Namskaket Creek and are generally composed of decaying plant material mixed with varying amounts of clay, silt, and sand. Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from USGS, local Town records and data from previous investigations. Final aquifer parameters were determined through calibration to observed water levels and stream flows. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Town and water-level data.

The 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. This recharge rate is based on the most recent USGS information. 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 and measured discharge at municipal wastewater treatment facilities, water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within designated residential areas utilizing on-site septic systems. The model incorporates discharge from the Tri-Town septage facility based on effluent discharge at the facility site.

III.3 NAMSKAKET CREEK ESTUARY CONTRIBUTORY AREAS

Newly revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the Namskaket Creek estuary system (Figure III-1). Model outputs of MEP 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, and (c) to more closely match the sub-embayment segmentation of the tidal hydrodynamic model. The smoothing refinement was a collaborative effort between the USGS and the rest of the MEP Technical Team.   The MEP sub-watershed delineations for this watershed do not include 10 yr time of travel boundaries. Overall, six sub-watershed areas, including Flax, Ruth, Cliff, and Little Cliff Ponds, were delineated within the watershed to the Namskaket Creek estuary.

Table III-1 provides the daily freshwater discharge volumes for each of the subwatsheds 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 measured surface water discharges. The overall estimated freshwater inflow into the Namskaket Creek estuary from its MEP watershed is 17,163 m3/d.

The delineations completed by this revised MEP analysis are the second watershed delineation completed in recent years for this estuary. A pre-MEP delineation was completed by the Cape Cod Commission and was defined based on regional water table measurements collected from available wells over a number of years and normalized to average conditions. This analysis included data collected in Leab, et al. (1995). The Commission's delineation was incorporated into the Commission's regulations through the Regional Policy Plan (CCC, 1996 & 2001). Figure III-2 compares the Commission delineation with the MEP delineation. The current revised watershed delineation adds refined watershed delineations to the upgradient ponds (Flax, Ruth, Cliff, and Little Cliff). The current watersheds to Cliff, Little Cliff, and Ruth ponds were previously identified during the course of the Pleasant Bay MEP analysis (Howes, et al., 2005).

Overall, the MEP contributing areas to the Namskaket Creek estuary based upon the groundwater modeling effort is very similar in area to the previous delineations based upon available well data. The watershed area for the MEP delineation is 2,237 acres, while the watershed delineated by the CCC is 2660 acres. The more refined watersheds to the ponds in the upper watershed in the MEP delineation create most of the difference between the two delineations.

The watershed to Namskaket Creek extends into portions of two towns: Brewster and Orleans. In order to accurately account for the area of the watershed in each town, MEP staff adjusted the areas upgradient of the freshwater ponds to account for the portion of the downgradient flow out of the ponds that stays within the watershed.   Based on these adjustments, 1,946 acres of the watershed is in the Town of Brewster and 290 acres are within the Town of Orleans.
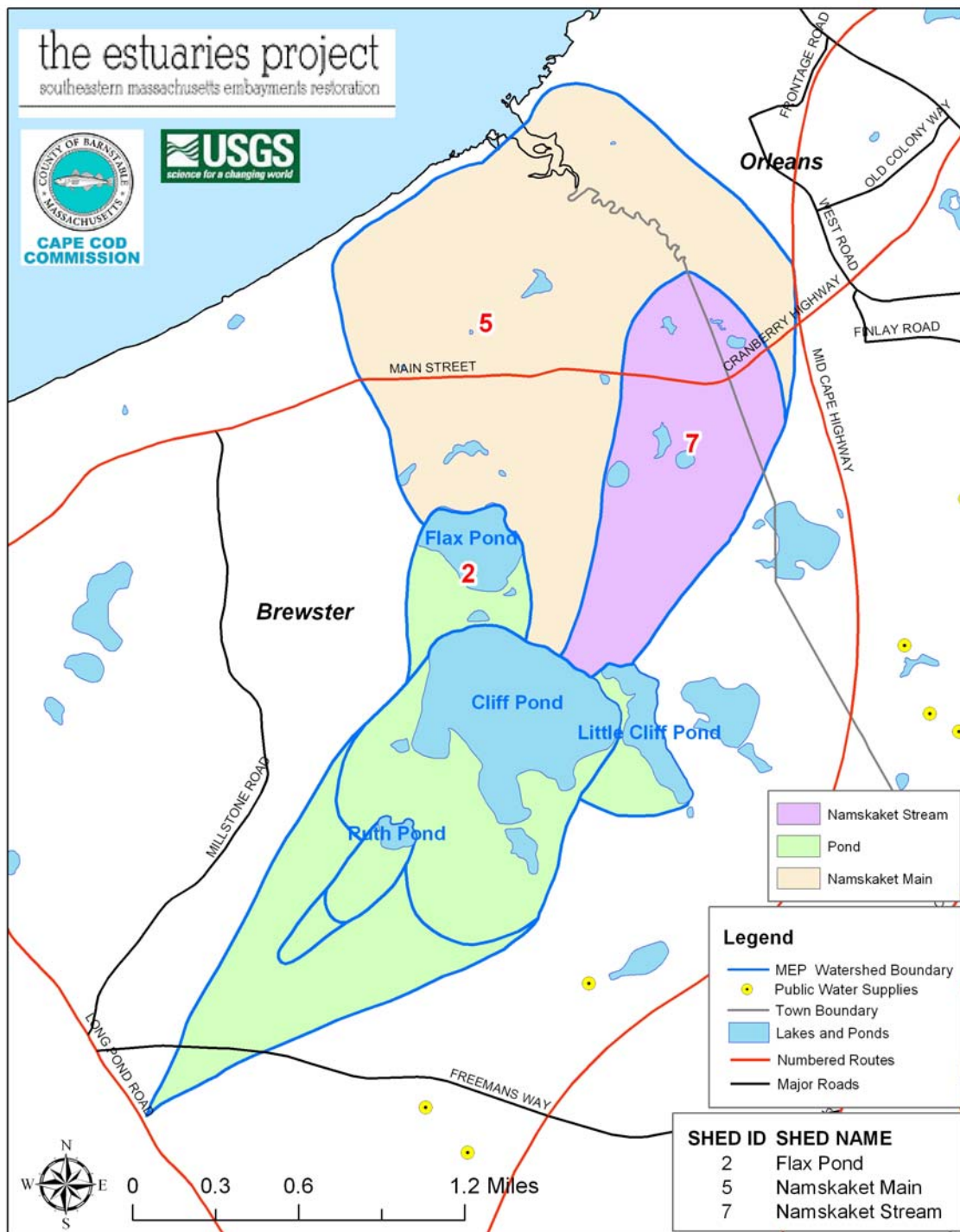
Figure III-1.   Watershed delineation for Namskaket Creek estuary. Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI). Assigned watershed numbers are based on delineation of all Cape Cod Bay estuaries in Town of Orleans. Watersheds to Cliff, Little Cliff, and Ruth Ponds were previously delineated during the MEP analysis of Pleasant Bay (Howes, *et al.*, 2005).

Table III-1.		Daily groundwater discharge to each of the sub-watersheds in the watershed to the Namskaket Creek estuary, as determined from the USGS groundwater model.			
Watershed	**#**	Watershed Area (acres)	% contributing to Creek	**Discharge**	
				m³/day	**ft³/day**
Flax Pond	2	118	87	785	27,738
Namskaket Main	5	1,039	100	7,977	281,707
Namskaket Stream	7	413	100	3,172	112,020
Little Cliff Pond*		283	16	4,880	12,324
Cliff Pond*		840	76	349	172,320
TOTAL				17,163	606,109

*Little Cliff and Cliff Pond delineations were completed for the Pleasant Bay MEP Technical Report (Howes, et al., 2005); Cliff contains the delineation to Ruth Pond.
Note: discharge volumes are based on 27.25 in of annual recharge over the watershed area; upgradient ponds often discharge to numerous downgradient subwatersheds, percentage of outflow is determined by length of downgradient shoreline going to each subwatershed

The evolution of the watershed delineations for the Namskaket Creek estuary 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 used for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon the land-uses that are included/excluded within the contributing areas. Small errors in watershed area can result in large errors in loading if a large source is counted in or out. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the downgradient estuary.
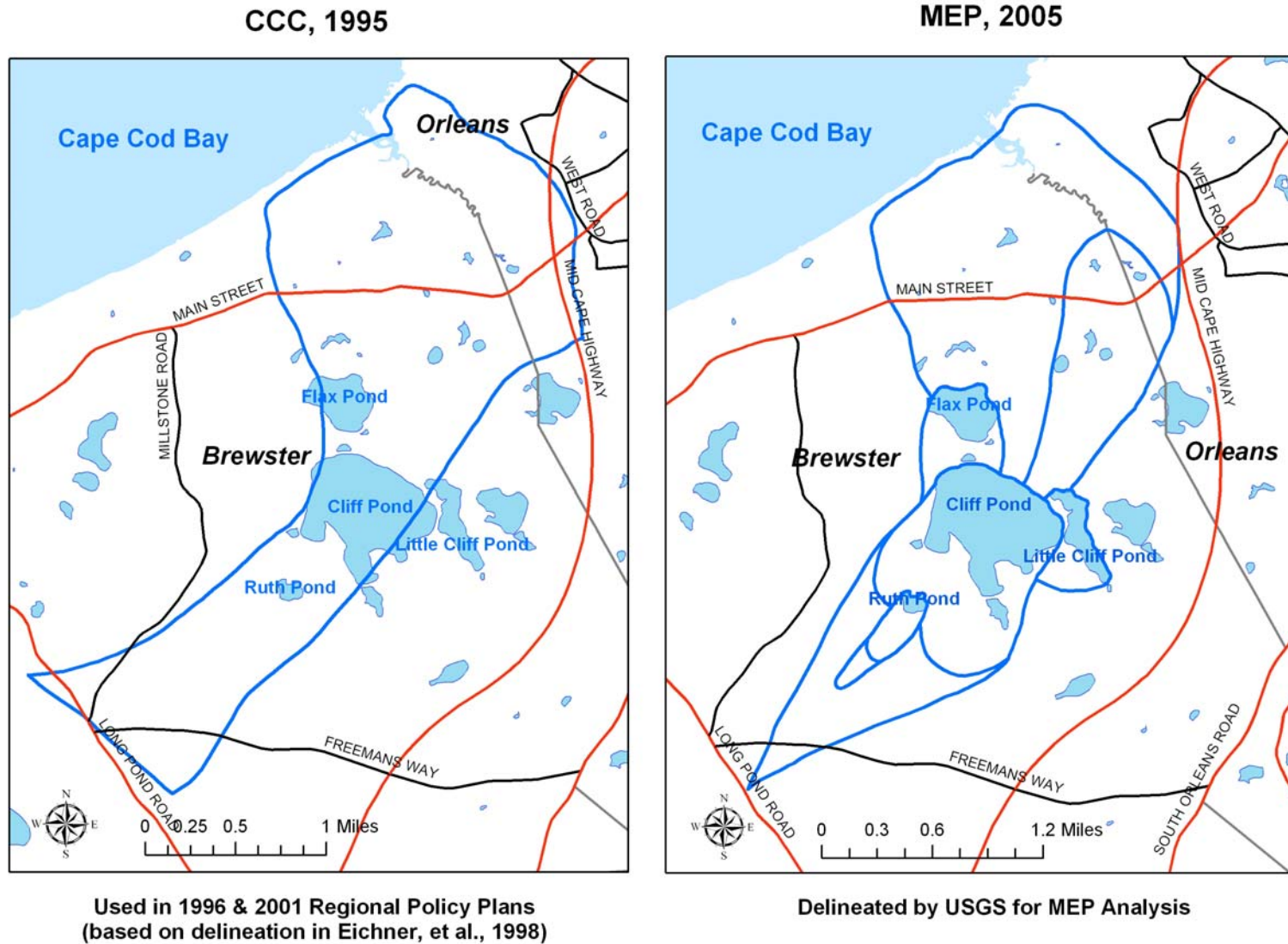
Figure III-2. Comparison of watershed and subwatershed delineations used in the current analysis and the Cape Cod Commission delineation completed for the Regional Policy Plan (CCC, 1996 & 2001).

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

The MEP Technical Team includes technical staff from the Cape Cod Commission (CCC). With the assistance of CCC Geographic Information System (GIS) staff , MEP Technical Team members developed nitrogen-loading rates (Section IV.1) to the Namskaket Creek estuary system (Section III). The Namskaket Creek watershed was sub-divided to define contributing areas to each of the major inland freshwater systems and to each major sub-estuary to Namskaket Creek. A total of six sub-watersheds were delineated for the Namskaket Creek Estuarine System, three of which are new delineations and three were previously delineated for the MEP Technical Report on Pleasant Bay (Howes, *et al.*, 2005). The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and each portion of the embayment (see Chapter III).

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the embayment. This involves a temporal review of land use changes, the time of groundwater travel provided by the USGS watershed model, and review of data at natural collections points, such as streams and ponds. Ten year time of travel zones are a regular part of the watershed analysis, but for Namskaket Creek all travel below Cliff Pond is within a ten year travel time and only a portion of the Cliff Pond watershed takes more than 10 years to reach the pond and included in this area is a subwatershed to Ruth Pond (Figure IV-1). The load in the portion of the watershed beyond 10-year time of travel to Cliff Pond is 43% of the pond's current loading (Howes, et al., 2005). However, this load is less than

10% of the overall unattenuated load to Namskaket Creek. MEP staff also reviewed land use development records for the age of developed properties in the watershed. Based on all these reviews and since the nitrogen load to Namskaket Creek from the ponds is based on their discharged attenuated load, it was determined that Namskaket Creek is currently in balance with its watershed load. The overall result of the timing of development relative to groundwater travel times is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuaries (after accounting for natural attenuation, see below).

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other detailed studies is applied to other portions. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon subwatershed-specific land uses and pre-determined nitrogen loading rates. For the Namskaket Creek embayment system, the model used Town of Orleans and Town of Brewster land-use data transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as parcel by parcel water use or groundwater monitoring wells). Determination of the nitrogen loads required obtaining watershed specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the "potential" or unattenuated nitrogen load to each receiving embayment, since attenuation during transport has not yet been included.

Natural attenuation of nitrogen during transport from land-to-sea (Section IV.2) within the Namskaket Creek System watershed was determined based upon a site-specific study of streamflow from the upper portion of the watershed (*i.e.*, Namskaket Stream) and flow coming from the Cliff Pond, Little Cliff Pond, Ruth Pond, and Flax Pond. Subwatersheds to these various portions allowed comparisons between field collected data from the streams and ponds and estimates from the nitrogen-loading sub-model. Attenuation through the ponds were developed based on site specific datasets collected by volunteers and currently under review by the SMAST under contract to the CCC or, if no data was available, conservatively assumed to equal 50% based on available monitoring of other Cape Cod lakes. Streamflow and associated surface water attenuation is included in the MEP's nitrogen attenuation and freshwater flow investigation, presented in Section IV.2.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. In the present effort, measurements were made of attenuation in Cliff Pond, Little Cliff Pond, Flax Pond and in the stream leading into the estuary portion of Namskaket Creek. There are a number of smaller ponds within the watershed without subwatershed delineations. However, if smaller aquatic features that have not been included in this MEP analysis are providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (<10%) overestimated given the distribution of nitrogen sources within the watershed. Based upon these considerations, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the one sub-watershed that directly discharges groundwater to the estuary without flowing through one of the interim measuring points. Internal nitrogen recycling was also determined throughout the tidal reaches of the Namskaket Creek Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval

and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).
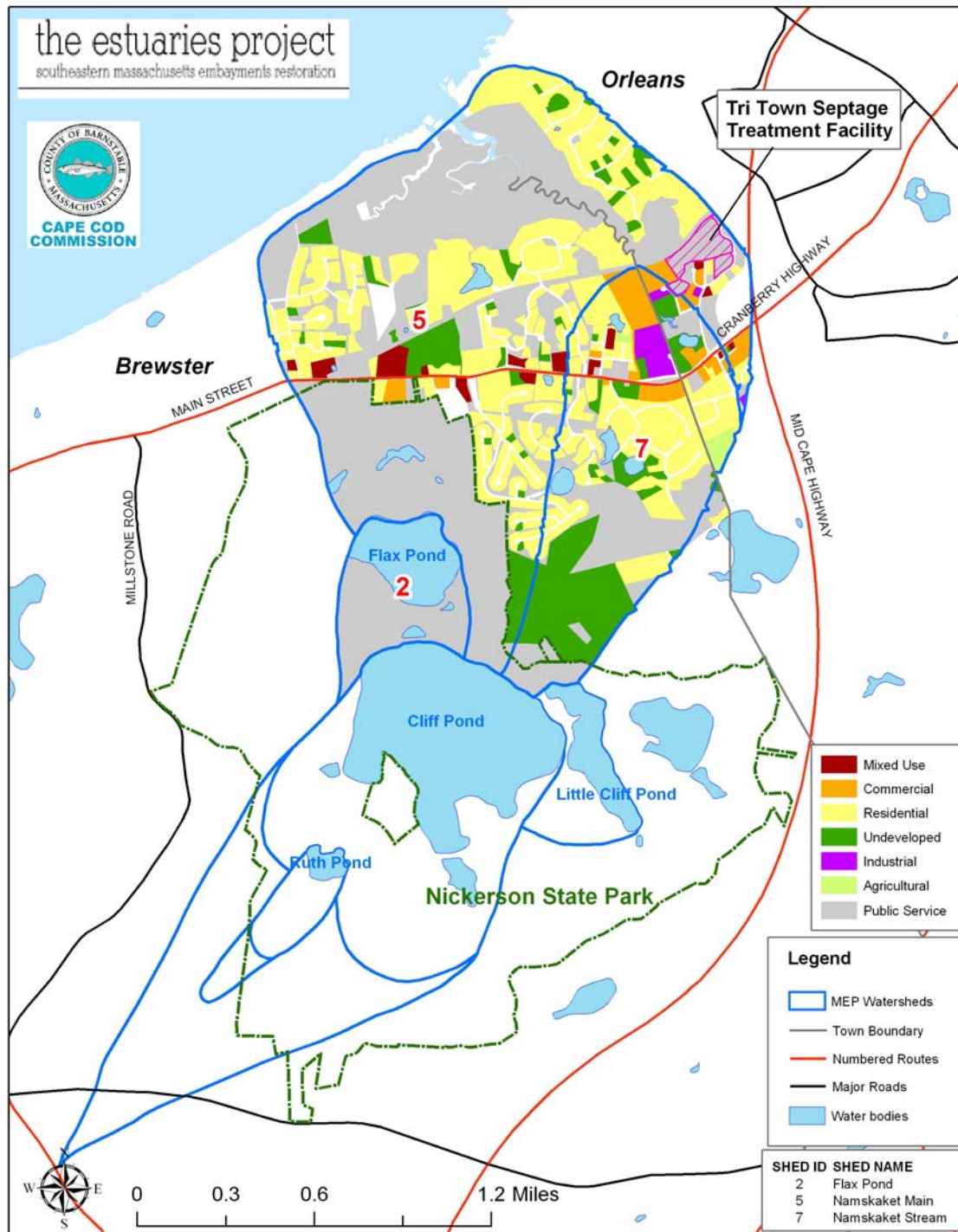
Figure IV-1.   Land-use in the Namskaket Creek estuary watershed.   The watershed extends into portions of both the Town of Orleans and the Town of Brewster. Land use classifications are based on assessors' records provided by the towns.

IV.1.1 Land Use and Water Use Database Preparation

Estuaries Project staff obtained digital parcel and tax assessors' data from the Towns of Orleans and Brewster. Digital parcels and land use data are from 2005 for Orleans and 2004 for Brewster and were obtained from the respective town planning departments and Cape Cod Commission files. These land use databases contain traditional information regarding assessor land use classifications (MADOR, 2002) plus additional information developed by each of the towns. The parcel data and assessors' databases for all the towns were combined for the MEP analysis by using the Cape Cod Commission Geographic Information System (GIS).

Figure IV-1 shows the land uses within the Namskaket Creek Estuary watershed area. Land uses in the study area are grouped into eight land use categories: 1) residential, 2) commercial, 3) industrial, 4) undeveloped, 5) agricultural, 6) public service/government, including road rights-of-way, 7) mixed use, and 8) freshwater features (e.g. ponds and streams). These land use categories, except the freshwater features, are aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2002). These categories are common to both towns in the watershed. "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (e.g., wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges.

In the portion of the Namskaket Creek System watershed, the predominant land use based on area is public service/government, which accounts for 53% of the overall watershed area (Figure IV-2). The high percentage of public service/government land is predominantly due to Nickerson State Park covering most of the upper watersheds to the freshwater ponds and a large portion of the lands around the creek itself being owned by the towns (Figure IV-1). Residential development accounts for the next highest percentage land uses area at 25%. Residential parcels are the predominant parcel type, accounting for 75% of the parcels in the watershed. Single-family residences (MADOR land use code 101) are 92% of the residential parcels and single-family residences are 90% of the residential land area. In the individual subwatersheds, residential land uses vary between 0 and 30% of the subwatershed areas, while public service/government land uses vary between 33 and 60%. Undeveloped areas generally account for less than 10% of the subwatershed areas except for the Namskaket Stream subwatershed where 23% of the watershed is undeveloped; the town assessors classify 73% of this as undevelopable. Overall, undeveloped land uses account for 7% of the entire Namskaket Creek watershed, while commercial properties account for approximately 2% of the watershed area.

In order to estimate wastewater flows within the Namskaket Creek study area, the MEP Technical Team obtained parcel-by-parcel water use information from the Towns of Brewster and Orleans. The water use data includes information from the Orleans Water Department via the Planning Department and the Brewster Water Department. Orleans water data is twelve months of water use between 2002 and 2003, while Brewster water data is three years between 2002 and 2004. There are no wastewater treatment facilities in the watershed, but the Tri Town Septage Treatment Facility discharges within the Namskaket Main subwatershed. MEP staff linked water use information to the parcel and assessors data using GIS techniques. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the measured water-use, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2).
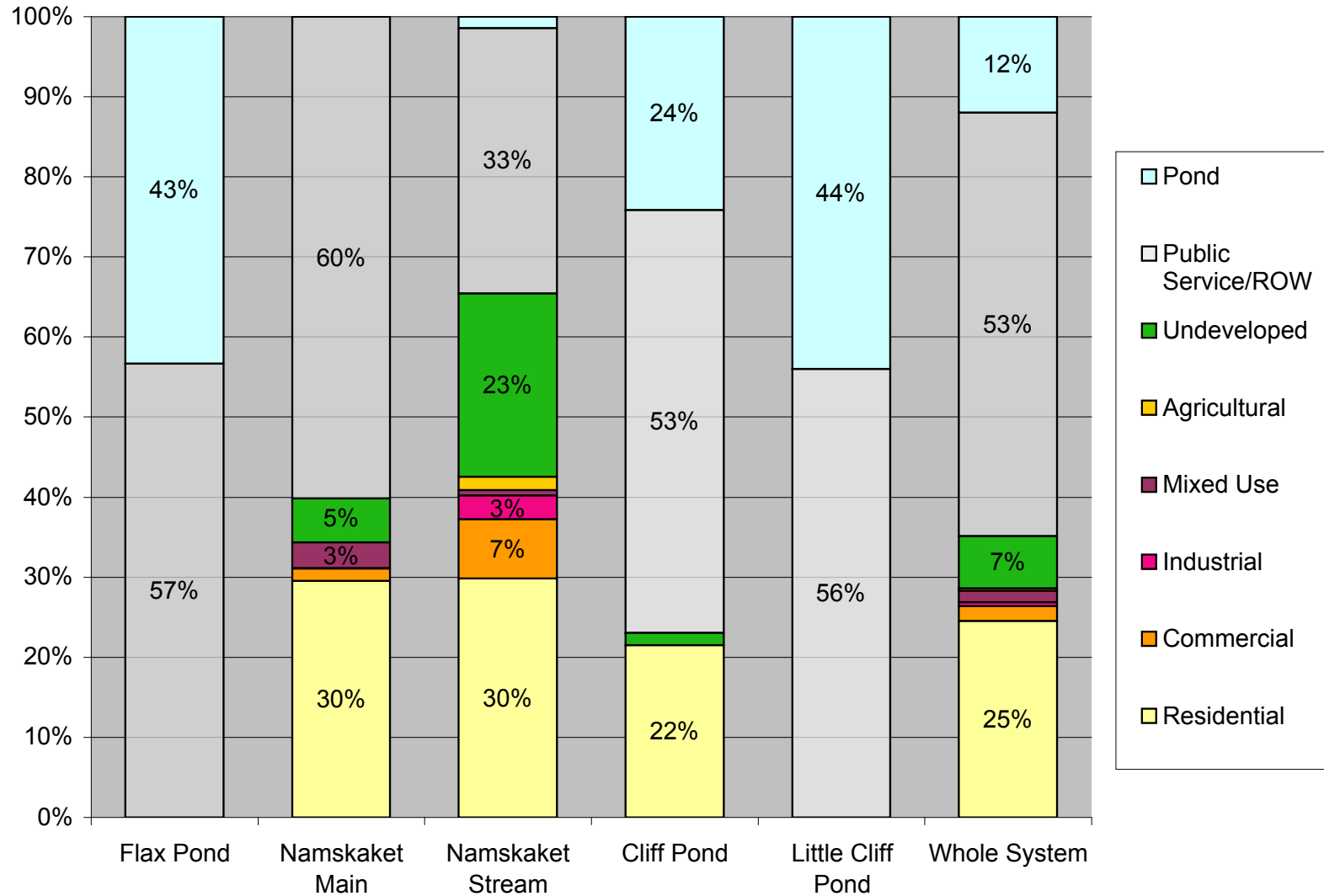
Figure IV-2. Distribution of land-uses within the major subwatersheds and whole watershed to Namskaket Creek. Only percentages greater than or equal to 3% are shown.

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

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

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

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

The nitrogen loads developed using this approach have been validated in a number of long and short term field studies where integrated measurements of nitrogen discharge from watersheds could be directly measured. Weiskel and Howes (1991, 1992) conducted a detailed watershed/stream tube study that monitored septic systems, leaching fields and the transport of the nitrogen in groundwater to adjacent Buttermilk Bay. This monitoring resulted in estimated annual per capita nitrogen loads of 2.17 kg (as published) to 2.04 kg (if new attenuation information is included). Modeled and measured nitrogen loads were determined for a small sub-watershed to Mashapaquit Creek in West Falmouth Harbor (Smith and Howes, manuscript

in review) where measured nitrogen discharge from the aquifer was within 5% of the modeled N load. Another evaluation was conducted by surveying nitrogen discharge to the Mashpee River in reaches with swept sand channels and in winter when nitrogen attenuation is minimal. The modeled and observed loads showed a difference of less than 8%, easily attributable to the low rate of attenuation expected at that time of year in this type of ecological situation (Samimy and Howes, unpublished data).

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

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

The independent validation of the water quality model (Section VI) 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 the how the septic system nitrogen mass compares to the nitrogen loads from all other sources that reach the estuary (i.e. attenuated loads).

In order to provide an independent validation of the average residential water use within the Namskaket Creek System watershed, MEP staff reviewed US Census population values for

the Towns of Brewster and Orleans. 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 Brewster is 2.45 people per housing unit, while year-round occupancy of available housing units is 56%. Orleans had an average occupancy of 2.05 people per housing unit and a 61% year-round occupancy of available housing units. Average water use for single-family residences with municipal water accounts in the Namskaket Creek watershed is 141 gpd. If 0.9 to account for consumptive use multiplies this flow, the watershed average water use is 126 gpd. If this flow is then divided by 55 gpd, the average estimated occupancy in the watershed is 2.3 people per household. If the Census occupancy rates for the towns are weighted by their proportion of the watershed areas, the resulting occupancy is 2.4. Given all of this analysis, MEP staff determined that the average water use for the watershed was reasonable and was an appropriate estimate for properties with wells and 92 additional residential dwellings estimated for the buildout scenario.

Water use information exists for 60% of the approximately 805 developed parcels in the Namskaket Creek watershed. The remaining 40% of the parcels (324 developed parcels) are assumed to utilize private wells for drinking water. These are properties that were 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, and do not have a listed account in the water use databases. Of the 324 parcels, 91% of them (294) are classified as single-family residences (land use code 101) and another eight parcels are classified as other types of residential development [e.g. 109 (multiple houses on a single property)]. The remaining 7% of the parcels are commercial and industrial properties (300s and 400s land use codes, respectively). MEP staff used current water use to develop a watershed-specific water use estimate for all uses that were assumed to utilize private wells.

Tri Town Septage Treatment Facility
As mentioned above, the Tri Town Septage Treatment Facility is located in Orleans on a 26 acre parcel at the head of the Namskaket salt marshes and discharges within the "Namskaket Main" subwatershed (Figure IV-1). The Tri-Town Facility is operated by the Orleans-Brewster-Eastham Groundwater Protection District and provides septage treatment services to the three listed towns as well as other Cape communities (Wright-Pierce, *et al.*, 2004). Monitoring of the discharge from the facility and its resulting groundwater plume of treated effluent has been coordinated for a number of years by the US Geological Survey (e.g., DeSimone, *et al.*, 1998).

In order to gauge the potential impact of the Tri Town effluent, MEP staff reviewed 2004 to 2006 flow and total nitrogen data provided by MassDEP (B. Dudley, personal communication, January 2007). Effluent flows between 2004 and 2006 averaged approximately 29,000 gallons per day or 10.6 million gallons per year (Figure IV-3). Total nitrogen load from the effluent averages 1,196 kg per year with a range of 1,126 to 1,275 kg N/yr. The current permitted discharge is 3,120 kg N/yr (Groundwater Discharge Permit No. 0-187; 45,000 gpd @ 50 mg N/L), although due to practical realities of seasonal flows the functional permitted discharge is more likely 2,280-2,660 kg N/y (calculated from Wright Pierce 2005).

Past characterizations of the geology and groundwater monitoring downgradient of the Tri Town facility suggests that the plume of groundwater impacted by the effluent from the facility has not reached Namskaket Marsh (*e.g.*, Weiskel, *et al.*, 1996). Monitoring of the groundwater plume

has been limited since the completion of these detailed characterizations, so there is some uncertainty about whether the plume has discharged into Namskaket Creek.

A significant part of the uncertainty results from the discovery of an as yet not fully defined, confining clay layer within the nearfield flow path of the plume. This clay layer, which was not within the original siting survey work for Tri-Town Facility appears to be altering the trajectory of the plume and likely the location of its eventual discharge. Although the leading edge of the clay layer and the plume have been characterized, the remainder, including the likely discharge area have not been fully characterized. Water quality sampling in Namskaket Creek between 2001 and 2006 shows no evidence that the plume was discharging to in any substantive way.

However, more recent groundwater modeling (particle tracking) by the USGS, under funding from Barnstable County, indicates the potential for the plume to eventually discharge to Namskaket Marsh and to a lesser extent, Little Namskaket Marsh. Therefore, MEP staff developed the above loading estimate for the facility and tested a number of scenarios through the linked-water quality model with and without the load from the Tri Town facility. The primary finding discussed in Chapter VIII, is that under present loading conditions, the Namskaket Marsh Estuary is below its nitrogen threshold load and that should the Tri Town treated effluent plume begin to discharge to the upper salt marsh, the system would still remain well below that threshold.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and cranberry bogs, with lawns being the predominant source within this category. In order to add this source to the nitrogen loading model for the Namskaket Creek system, MEP staff reviewed available information about residential lawn fertilizing practices and incorporated site-specific information to determine nitrogen loading from large tracks of turf in the watershed. Residential lawns are the only source of fertilizer load identified in the Namskaket Creek estuary watershed.

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

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. The assessment accounted for proximity to fresh ponds and embayments. Based upon ~300 interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sq. ft., 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a leaching rate of 20% results in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors are generally used in the MEP nitrogen loading calculations. It is likely that this still represents a conservative estimate of nitrogen load from residential lawns. It should also be noted that professionally maintained lawns were found to have the higher rate of fertilizer application and hence higher estimated loss to groundwater of 3 lb/lawn/yr.
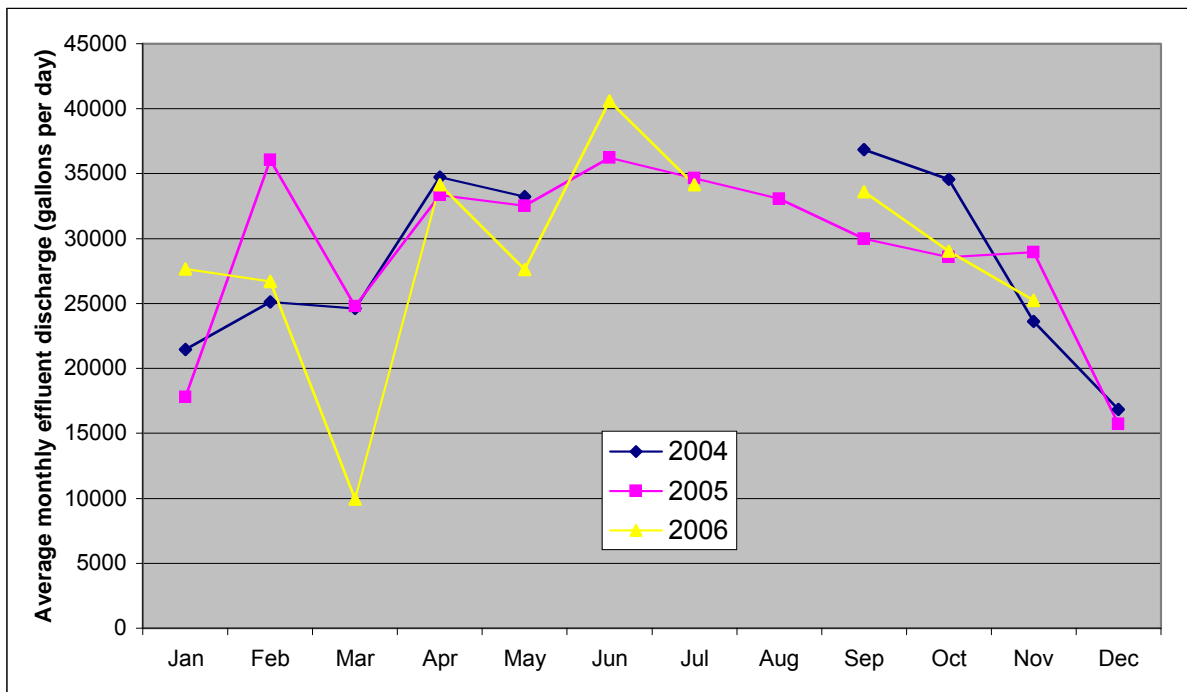
a. Effluent discharge at the Tri Town Septage Facility (2004-2006)
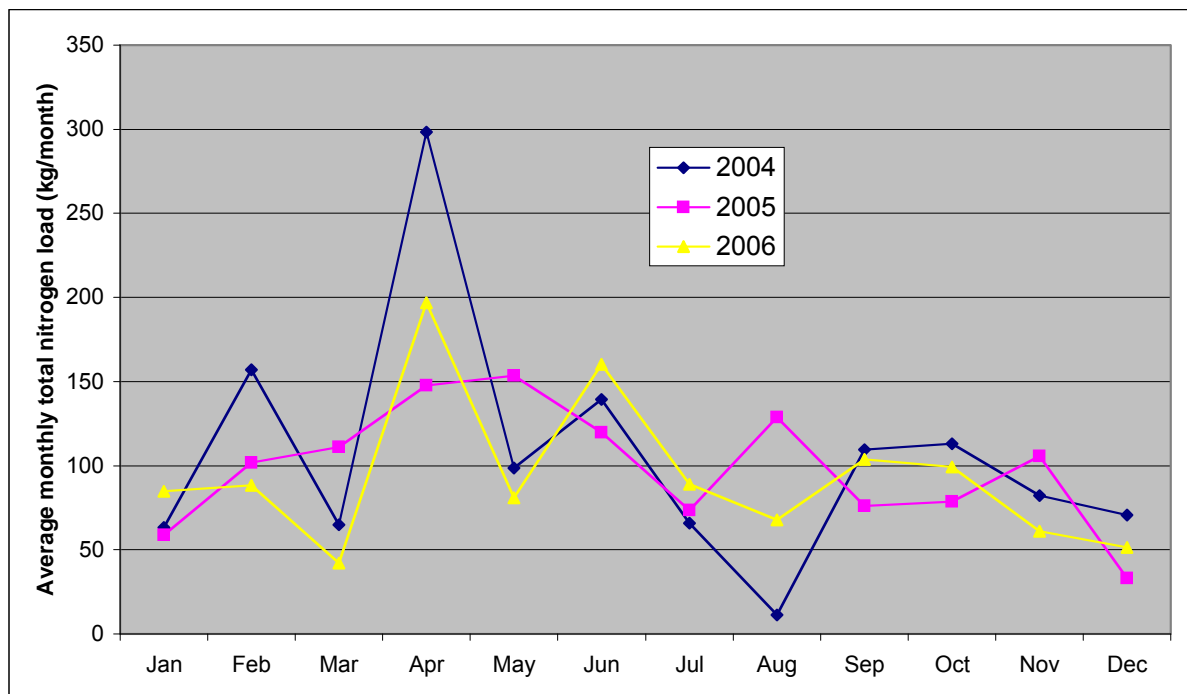
b. Total Nitrogen effluent loading at the Tri Town Septage Facility (2004-2006)

Figure IV-3.   Effluent flow (a) and nitrogen loading (b) from the Tri Town Septage Facility (2004-2006). Data provided by MassDEP.

Although the above values are generally used in MEP modeling, the Orleans Wastewater Planning Committee conducted a 2003 survey of 340 homes throughout the Town of Orleans. The results of this survey indicated that the number of fertilizations per lawn in Orleans was similar to the number listed above, 1.76 versus 1.44, but there were a very high number of homes serviced by commercial lawn companies (over 1/3). These commercially-tended lawns were fertilized at higher rate than those developed above for standard homeowner-tended lawns. The overall results indicated potentially higher nitrogen loading per lawn in Orleans of 1.51 lb/lawn/yr (weighted average). MEP staff used this higher application rate based on this site-specific information.

Nitrogen Loading Input Factors: Other

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

Table IV-1.	Primary Nitrogen Loading Factors used in the Namskaket Creek MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Barnstable data. *Data from Orleans lawn study.		
Nitrogen Concentrations:	**mg/l**	**Recharge Rates:**	**in/yr**
Road Run-off	1.5	Impervious Surfaces	40
Roof Run-off	0.75	Natural and Lawn Areas	27.25
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:	
Natural Area Recharge	0.072	Existing developed residential parcels wo/water accounts and buildout residential parcels:	141 gpd
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (sq ft)*	5,000		
Residential Watershed Nitrogen Rate (lbs/lawn)*	1.51	Existing developed parcels w/water accounts:	Measured annual water use
Nitrogen leaching rate	20%	Buildout additions:	
Impervious Surfaces (based on ORL data):		Commercial wastewater	98 gpd/1,000 ft2 of building
Residences (sq ft):	2056	Industrial wastewater	16 gpd/1,000 ft2 of building
Commercial building coverage for parcels:	13%		
Industrial building coverage for parcels:	10%	Average Tri Town N load (kg/y)	1,196

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, parcels were assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel was located within a respective watershed. Following the assigning of

boundary parcels, all large parcels were examined individually and were split (as appropriate) in order to obtain less than a 2% difference between the total land area of each subwatershed and the sum of the area of the parcels within each subwatershed. The resulting "parcelized" watersheds to Namskaket Creek are shown in Figure IV-4.

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, Tri Town facility, 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 Namskaket Creek estuary. The assignment effort was undertaken to better define the sub-embayment loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Following the assignment of all parcels, subwatershed modules were generated for each of the three new sub-watersheds summarizing water use, parcel area, frequency, sewer connections, private wells, and road area. The three subwatershed modules for Cliff, Little Cliff, and Ruth Ponds were previously developed for the MEP Technical Report on Pleasant Bay (Howes, *et al*., 2005). The individual sub-watershed modules were then integrated to create the Namskaket Creek Watershed Nitrogen Loading module with summaries for each of the individual portions (or subestuaries) of the larger system. The subestuaries represent the functional embayment units for the Linked Watershed-Embayment Model's water quality component.

For management purposes, the aggregated embayment watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Namskaket Creek System, the major types of nitrogen loads are: wastewater (e.g., septic systems), the Tri Town facility, fertilizer, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-5 a-c). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model.

Since groundwater outflow from a pond can enter more than one downgradient sub-watershed, the length of shoreline on the downgradient side of the pond was used to apportion the pond-attenuated nitrogen load to respective downgradient watersheds. The apportionment was based on the percentage of discharging shoreline bordering each downgradient sub-watershed. So for example, Flax Pond has a downgradient shoreline of 3,042 feet; 87% of that shoreline discharges into the Namskaket Creek subwatershed (watershed 5 in Figure IV-1) and 13% discharges outside of the overall Namskaket Creek watershed. The attenuated nitrogen load discharging from Flax is divided among these subwatersheds based on these percentages of the downgradient shoreline.
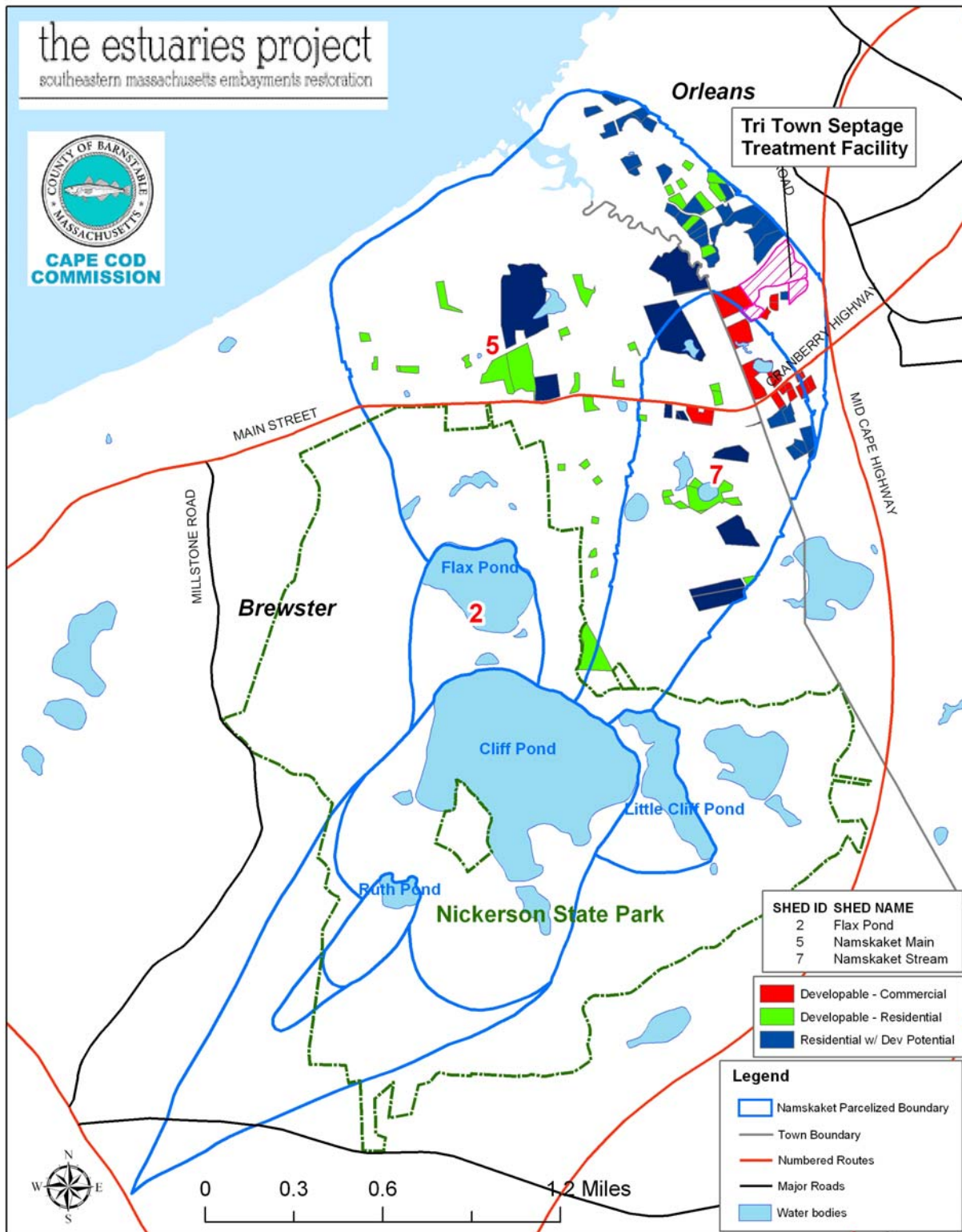
Figure IV-4.   Parcels, Parcelized Watersheds, and Developable Parcels in the Namskaket Creek watersheds.

Table IV-2. Namskaket Creek Nitrogen Loads. Attenuation of Namskaket Creek system nitrogen loads occurs as nitrogen moves through upgradient ponds and streams during transport to the estuary. All values are kg N yr^{-1}. Version A does not include load from the Tri Town Septage Facility, while Version B includes load from the facility in the "From WWTF" column.

A. Watershed loading without WWTF loading from TriTown Septage Facility

Name	Watershed ID#	Namskaket Creek N Loads by Input (kg/y):							% of Pond Outflow	Present N Loads			Buildout N Loads		
		Wastewater	From WWTF	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Namskaket Creek System		3916	0	455	433	1040	381	5331		6225		4638	11556		9382
Namskaket Main Total	5+CP	2348	0	277	237	185	212	592		3259		3061	4486		3648
Namskaket Main	5	2170	0	260	217	0	194	583		2840		2840	3423		3423
Cliff Pond	CP	178	0	17	20	142	19	9	15%	376	50%	178	386	50%	183
Namskaket Creek Estuary surface deposition						43				43		43	43		43
Flax Pond Total	2+CP	535	0	53	60	625	68	238		1341	50%	373	1580	50%	485
Flax Pond	2	0	0	0	0	199	12	210	87%	210		210	421		421
Cliff Pond	CP	535	0	53	60	426	56	28	45%	1131	50%	535	1159	50%	549
Namskaket Stream Total	7+LCP,CP	1033	0	125	135	230	100	4500		1624	10%	1204	6125	10%	5249
Namskaket Stream	7	808	0	103	110	26	75	4489		1123		1123	5612		5612
Little Cliff Pond	LCP	46	0	5	5	62	6	2	16%	124	50%	36	126	50%	37
Cliff Pond	CP	179	0	18	20	142	19	9	15%	378	50%	179	387	50%	183

B. Watershed loading including WWTF loading from TriTown Septage Facility

Name	Watershed ID#	Namskaket Creek N Loads by Input (kg/y):							% of Pond Outflow	Present N Loads			Buildout N Loads		
		Wastewater	From WWTF	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Namskaket Creek System		3916	1196	455	433	1040	381	5331		7421		5834	12752		10578
Namskaket Main Total	5+CP	2348	1196	277	237	185	212	592		4455		4257	5682		4845
Namskaket Main	5	2170	1196	260	217	0	194	583		4036		4036	4619		4619
Cliff Pond	CP	178	0	17	20	142	19	9	15%	376	50%	178	386	50%	183
Namskaket Creek Estuary surface deposition						43				43		43	43		43
Flax Pond Total	2+CP	535	0	53	60	625	68	238		1341	50%	373	1580	50%	485
Flax Pond	2	0	0	0	0	199	12	210	87%	210		210	421		421
Cliff Pond	CP	535	0	53	60	426	56	28	45%	1131	50%	535	1159	50%	549
Namskaket Stream Total	7+LCP,CP	1033	0	125	135	230	100	4500		1624	10%	1204	6125	10%	5249
Namskaket Stream	7	808	0	103	110	26	75	4489		1123		1123	5612		5612
Little Cliff Pond	LCP	46	0	5	5	62	6	2	16%	124	50%	36	126	50%	37
Cliff Pond	CP	179	0	18	20	142	19	9	15%	378	50%	179	387	50%	183

a. Namskaket Creek System Overall
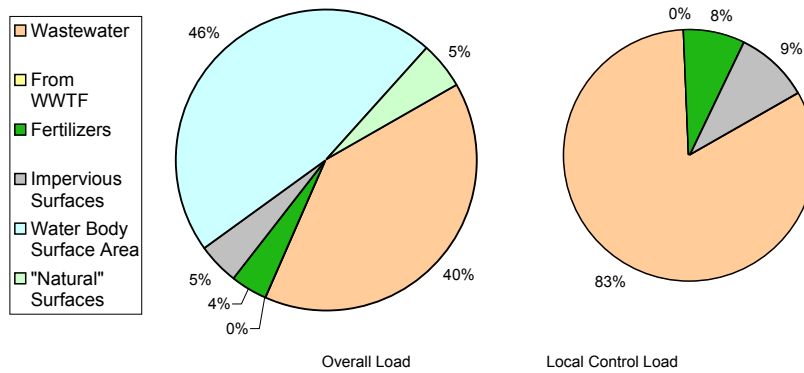
b. Flax Pond Subwatershed
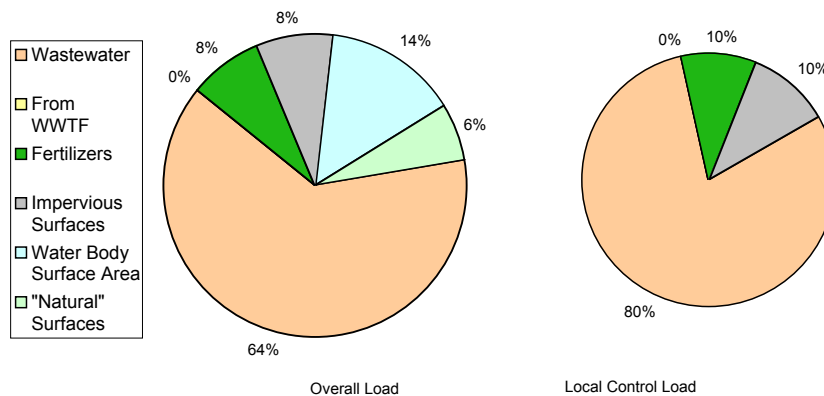
c. Namskaket Stream Subwatershed

Figure IV-5 (a-c). Land use-specific unattenuated nitrogen load (by percent) to the (a) overall Namskaket Creek System watershed (including load from the TriTown Septage Facility in the "From WWTF" category, (b) Flax Pond subwatershed, and (c) Namskaket Stream subwatershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.

Freshwater Pond Nitrogen Loads

Freshwater ponds on Cape Cod 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 upgradient shoreline, then lake water flows back into the groundwater system along the downgradient shoreline. Occasionally a Cape Cod pond will also have a stream outlet or 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 watershed system, mostly through burial in the sediments and denitrification that returns it to the atmosphere. Following these reductions, the remaining (reduced or attenuated) loads flow back into the groundwater system along the downgradient side of the pond or through a stream outlet and eventual discharge into the downgradient embayment. The nitrogen load summary in Table IV-2 includes both the unattenuated (nitrogen load to each subwatershed) and attenuated nitrogen loads.

Pond nitrogen attenuation in freshwater ponds has generally been found to be at least 50% in MEP analyses, so MEP watershed models generally contain a conservative attenuation rate of 50%. 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 (Three Bays MEP Report, 2005). In order to estimate nitrogen attenuation in the ponds physical and chemical data for each pond is reviewed. Available bathymetric information is reviewed relative to measured pond temperature profiles to determine whether thermal layering has occurs in a pond. Bathymetric information is necessary to develop a residence or turnover time and complete an estimate of nitrogen attenuation.

In the Namskaket Creek watershed, bathymetric information is available for the following ponds: Cliff, Little Cliff, Ruth and Flax. Of the ponds with bathymetric information, Cliff, Little Cliff, and Flax are deep enough to develop strong temperature stratification or layering. If temperature readings indicate that a pond is well mixed, generally samples from all depths can be used for determining average nitrogen concentrations. In ponds with stratification, deepest samples must be checked for potential impact by sediment regeneration of nitrogen, especially if low oxygen conditions occur.

In MEP analyses, available nitrogen concentrations from individual ponds are reviewed to establish whether sediment regeneration is a significant factor in a pond and, if not, the entire volume of the pond is used to determine a turnover time. Turnover time is how long it takes the recharge from the upgradient watershed to completely exchange the water in the pond or, in the case of a thermally stratified pond, exchange just the upper or epilimnion layer. The total mass of nitrogen in the pond or epilimnion is adjusted using the pond turnover time to determine the annual nitrogen load returned to the aquifer through the downgradient shoreline. This mass is then compared to the nitrogen load coming from the pond's watershed to determine the nitrogen attenuation factor for the pond.

In the Namskaket Creek watershed, the conservative, standard 50% attenuation rate was used for all ponds. Cliff, Little Cliff and Flax have field and laboratory data collected between 2001 and 2005 for these ponds by volunteers coordinated through the Cape Cod Pond and

Lake Stewardship (PALS) program. The laboratory data includes results from the annual PALS water quality snapshot, which is coordinated between the Cape Cod Commission and SMAST, and results from the National Park Service. The PALS Snapshot is a collaborative Commission/SMAST program that allows trained, citizen volunteers of each of the 15 Cape Cod towns to collect pond samples in August and September using a standard protocol. Snapshot samples have been collected every year between 2001 and 2008. PALS pond samples are analyzed at the SMAST laboratory for total nitrogen, total phosphorus, chlorophyll *a*, alkalinity, and pH. The standard protocol for the Snapshot includes field collection of dissolved oxygen and temperature profiles, Secchi disk depth readings and water samples at various depths depending on the total depth of the pond. The sampling protocol for the PALS Snapshot has been utilized for all sampling of the ponds for the data that was reviewed, which includes data collected throughout the summer, June through September. SMAST is currently reviewing all this data for the Town of Brewster under a contract with the Commission.

Table IV-3 summarizes the pond attenuation estimates calculated from land-use modeled nitrogen inflow loads and nitrogen loads recharged to the downgradient aquifer or to outflow streams from each pond in the Namskaket Creek watershed based on available pond characteristics and measured nitrogen levels. Nitrogen attenuation within the ponds with available data varies between 69 and 87%. Ruth Pond does not have monitoring data. All ponds are assigned the conservative, standard 50% attenuation.

Table IV-3. Nitrogen attenuation by Freshwater Ponds in the Namskaket Creek watershed based upon 2001 through 2006 sampling data collected by Brewster volunteers. These data were collected to provide a site-specific check on the conservative, standard 50% attenuation rate assigned to freshwater ponds in MEP analyses. The MEP Linked N Model for Namskaket Creek uses the 50% attenuation rate for all ponds.

Pond	PALS ID	Area acres	Maximum Depth m	Overall turnover time yrs	TN samples for Attenuation calculation	N Load Attenuation %
Cliff	BR-1028	201.9	26.8	3.4	53	69%
Little Cliff	BR-192	34.5	13.8	0.6	20	76%
Ruth	BR-209	7.5	4.6	0.4	0	50%*
Flax	BR-168	51.2	21.8	4.8	48	87%
				Mean	67%	
				std dev	21%	

*standard MEP freshwater pond attenuation rate; Ruth Pond has no sampling data available
Data sources: all areas from CCC GIS; Max Depth from MassDFW or Cape Cod PALS monitoring; Volume for turnover time calculations from MassDFW bathymetric maps (www.mass.gov/dfwele/dfw/dfw_pond.htm); TN concentrations for attenuation calculation from volunteer monitoring including lab data from annual PALS Snapshot provided by SMAST lab and data from NPS lab

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development within the study area watershed. For the Namskaket Creek modeling, MEP staff consulted with respective town officials to determine the information that would be used in the assessment. Orleans buildout information was provided by the town

Planning Department during the development of the Pleasant Bay MEP Technical Report; further communication with the Town Planner led to subsequent modification in the buildout parameters (G. Meservey, personal communication, February 2007). This change brought the buildout into congruence with buildout numbers being used in the current town Comprehensive Wastewater Management Plan process. Brewster buildout was completed with guidance from town officials and utilized standard MEP buildout parameters.

A standard MEP buildout assessment is to evaluate town zoning to determine minimum lot sizes in each of the zoning districts, including overlay districts (*e.g.*, water resource protection districts). Larger lots are subdivided by the minimum lot size to determine the total number of new lots and existing developed properties are reviewed for additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence. In the Brewster buildout completed by MEP staff, parcels that are classified by the town assessor as developable residential (state class land use codes 130 and 131) but are less than the minimum lot size and are greater than 5,000 square feet are assigned one residence in the buildout; 5,000 square feet is a common minimum buildable lot size in Cape Cod town regulations. Properties classified by the Brewster assessor as "undevelopable" (e.g., codes 132, 392, and 442) were not assigned any development at buildout; this is different than the assumption used in the Orleans buildout, for example. Commercially developable properties were not subdivided in any of the towns; the area of each parcel and the factors in Table IV-2 were used to determine a wastewater flow for these properties. All the parcels included in the buildout assessment of the Namskaket Creek watershed are shown in Figure IV-4. A nitrogen load for each additional parcel included in the buildout was developed using the factors in Table IV-1.

Overall, a cumulative nitrogen load for each additional residence or business is included in the unattenuated buildout indicated in a separate column in Table IV-2. The Tri Town Facility is not assigned any additional load at buildout. Buildout additions within the overall Namskaket Creek System watershed will increase the unattenuated loading rate by 86% in the scenario without the nitrogen load from the TriTown Septage Facility and 72% in the scenario including the load from the TriTown Facility.

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 Namskaket Marsh 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 region of the watersheds to these Town of Orleans systems). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification.

However, in most watersheds in southeastern Massachusetts, nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the case of the Orleans embayment system watersheds for Namskaket Marsh, a portion of the freshwater flow and transported nitrogen passes through a surface water system (Creek from Hurley's Bog to Namskaket Marsh) prior to entering estuarine system, producing the opportunity for nitrogen attenuation.

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

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, 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 head of the Namskaket Marsh embayment system considered in this report in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). The additional site-specific study was conducted in the 1 major surface water flow system in the watershed to the head of the marsh, 1) Creek discharging from Hurley's Bog to the head of Namskaket salt marsh (Figure IV-6).
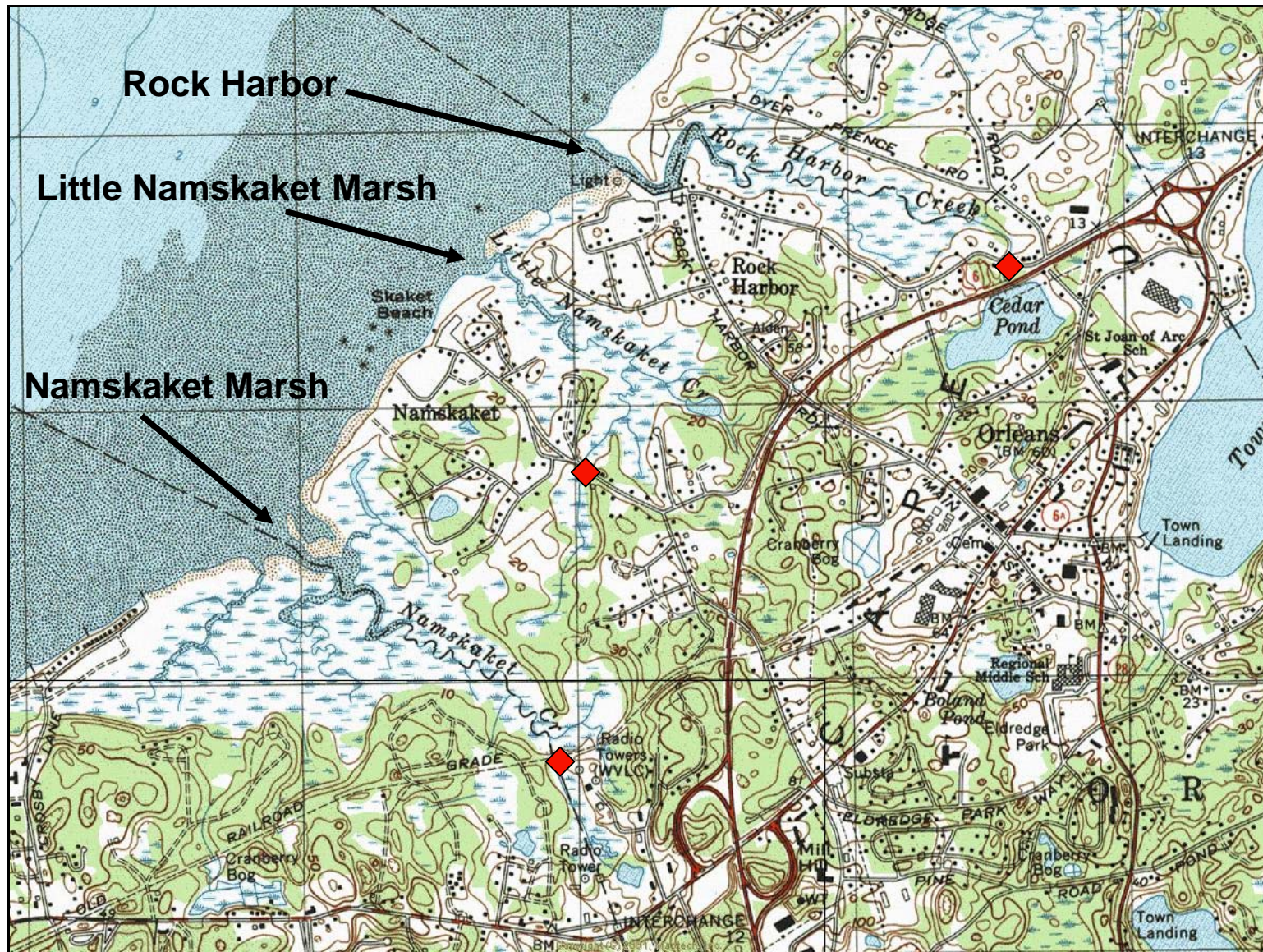
Figure IV-6.   Location of Stream gages (red symbols) in the Rock Harbor, Little Namskaket Marsh and Namskaket Marsh embayment systems.

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 up-gradient from the gauge site. Flow and nitrogen load was measured at the gage in the freshwater stream site for between 16 and 24 months of record (Figure IV-7, Table IV-4). During the study period, velocity profiles were completed on the stream every month to two months. The summation of the products of stream subsection areas of the stream cross-section and the respective measured velocities represent the computation of instantaneous stream flow (Q).

Determination of stream flow at the gage 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 gage 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 gages. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given river. These hourly stages values where 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. In the case of tidal influence on stream stage, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of strictly freshwater flow. The two low tide stage values for any given day were averaged and the average stage value for a given day was then entered into the stage – discharge relation in order to compute daily flow. A complete annual record of stream flow (365 days) was generated for the surface water discharge flowing into the Namskaket Marsh systems.
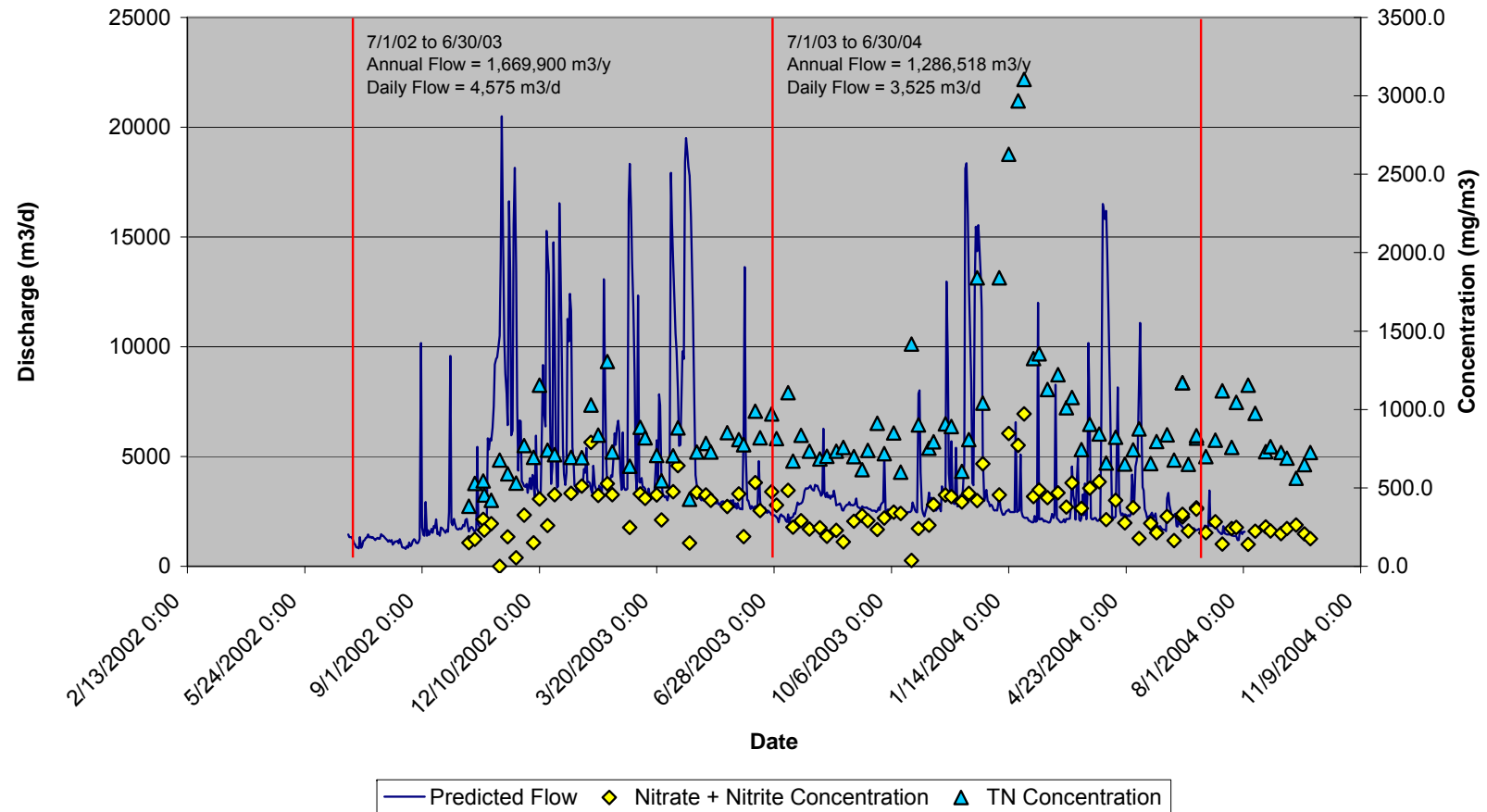
Figure IV-7.   Discharge from Hurley's (solid blue line), nitrate+nitrite (yellow diamonds) and total nitrogen (blue triangles) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Namskaket Marsh (Table IV-5).

Table IV-4. Comparison of water flow and nitrogen discharges from streams (freshwater) discharging to the head of each Orleans marsh. 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	Rock Harbor Cedar Pond Discharge[a]	Namskaket Hurley Bog Discharge[a]	Little Namskaket Stream Discharge[a]	Data Source
Total Days of Record	365[b]	365[b]	365[b]	(1)
Flow Characteristics				
Stream Average Discharge (m3/day) **	1271	4050	203	(1)
Contributing Area Average Discharge (m3/day)	1057	4499	282	(2)
Discharge Stream relative to Long-term Discharge	-20%	10%	28%	
Nitrogen Characteristics				
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.116	0.352	0.54	(1)
Stream Average Total N Concentration (mg N/L)	0.86	0.837	1.013	(1)
Nitrate + Nitrite as Percent of Total N (%)	13%	42%	53%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	1.09	3.39	0.21	(1)
TN Average Contributing UN-attenuated Load (kg/day)	2.62	4.45	0.41	(3)
Attenuation of Nitrogen in Pond/Stream (%)	58%	24%	49%	(4)

(a) Flow and N load to streams discharging to Orleans salt marsh systems includes apportionments of Pond contributing areas.
(b) September, 2002 to August, 2003 (Rock Harbor), July 2002 to June 2003 (Little Namskaket), July 2002 to June 2004 (Namskaket)
** Flow is an average of annual flow for 2002-2003

(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 streams to Orleans Marshes;
   and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates as applicable.
(4) Calculated based upon the measured TN discharge from the rivers vs. the unattenuated watershed load.

The annual flow record for the surface water flow at the gage was merged with the nutrient data set generated through the weekly water quality sampling performed at the gage location to determine nitrogen loading rates to the head of the marsh system. 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 gauging site. For the stream gage 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 each pond currently reduces (percent attenuation) nitrogen loading to the embayment system.

IV.2.2   Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge Hurley's Bog to head of Namskaket Marsh

Hurley's Bog is a wetland area located immediately up-gradient of the stream gage site. The stream outflow from the wetland up-gradient of the gage serves as a location for a direct measurement of the nitrogen attenuation occurring in the wetland. The rate of nitrogen attenuation by biogeochemical processes occurring in the wetland was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the wetland above the gage site and the measured annual discharge of nitrogen Namskaket Marsh relative to the gage, Figure IV-6.

At the Hurley Bog gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the discharge that carries nitrogen load from the wetland to the head of Namskaket Marsh. As the Hurley's Bog discharge is tidally influenced the gage was located as far above the saltwater reach such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average low tide salinity was determined to be 2.4 ppt. Based on the low salinity, the gage location was deemed acceptable for making freshwater flow measurements at low tide. Calibration of the gage was checked monthly. The gage on the stream outflow from Hurley's Bog was installed on June 29, 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 26 months. The 12-month uninterrupted record (hydrologic year low flow to low flow) used in this analysis is an average of two years of flow and water quality monitoring at the stream gage covering the period 2002-2003 and 2003-2004.

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Hurley Bog stream gage site based upon these flow measurements and measured water levels at the gage 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 head of Namskaket marsh (Figure IV-7 and Table IV-4). 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 each gage site.

The annual freshwater flow record for the stream from Hurley Bog 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 Hurley Bog was 10% below the long-term average modeled flows. Measured flow in the stream from Hurley Bog was obtained for two hydrologic years (July 2002 to June 2003 and July 2003 to June 2004). The average daily flow based on the MEP measured flow data was 4,050 m^3/day compared to the long term average flows determined by the USGS modeling effort (4,499 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 the Hurley Bog stream are in part be due to below average rainfall during the year prior to the deployment as well as during the first part of the stream gage deployment period based on rainfall records obtained from a rain gage in the Town of Chatham. Thirteen years of rainfall data (1993-2006) indicate that the average rainfall in the vicinity of the Namskaket Marsh system was 45.1 inches. By comparison, rainfall in 2001, the year before the gage deployment, was 33.8 inches. Rainfall in 2002 was 57.3 inches (above long term average) and the rainfall in 2003 was 40.8 inches (below long term average). It should be recognized that although 2002 rainfall was above average, the water table is likely to have been lower than usual due to the prior year of lower rainfall. This is significant relative to measured flow in the Creek surface water system discharging to Namskaket Marsh as it is essentially a groundwater fed feature. Based upon the rainfall and groundwater levels associated with the stream measurement (suggesting a lower flow than the long-term average) and the some what lower measured stream discharge then predicted (-10%) it appears that the stream is capturing the upgradient recharge (and loads) accurately.

Total nitrogen concentrations within the Hurley Bog stream outflow were low, 0.837 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 3.39 kg/day and a measured total annual TN load of 1,238 kg/yr. In the Hurley Bog surface water system, nitrate was slightly less than half of the total nitrogen load (42%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the wetland or stream ecosystems. The moderate concentration of inorganic nitrogen in the out-flowing stream waters also suggests that plant production within the up-gradient freshwater ecosystems is not nitrogen limited. In addition, the nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system within the wetland up-gradient of the Hurley Bog stream gage.

From the measured nitrogen load discharged by Hurley Bog to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower nitrogen load (1,238 kg yr^{-1}) discharged from the freshwater Hurley Bog compared to that added by the various land-uses to the associated watershed (1,624 kg yr^{-1}), the integrated attenuation in passage through the wetland prior to discharge to the estuary is 24% (i.e. 24% of nitrogen input to watershed does not reach the estuary). This slightly lower level of attenuation compared to other streams evaluated under the MEP is expected given the hydraulic nature of the up-gradient wetland (relatively high flow which is essentially passed through a shallow wetland system combined with a lack of ponds in the sub-watershed to this gage). The directly measured nitrogen loads from the stream was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

Table IV-5.   Summary of annual volumetric discharge and nitrogen load from the Rivers and Streams (freshwater) discharging to the Town of Orleans systems based upon the data presented in Figures IV-7 and Table IV-4.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Cedar Pond Stream (MEP)	September 1, 2002 to August 31, 2003	463762	54	399
Cedar Pond Stream (CCC)	Based on Watershed Area and Recharge		--	--
Hurley Bog Stream (Freshwater) MEP	July 1, 2002 to June 30, 2003 July 1, 2003 to June 30, 2004 Average	1669900 1286518 1478209	549 492 521	1175 1302 1239
Hurley Bog Stream (Freshwater) CCC	Based on Watershed Area and Recharge		--	--
Stream to Little Namskaket (Freshwater) MEP	July 1, 2002 to June 30, 2003	74033	40	75
Stream to Little Namskaket (Freshwater) CCC	Based on Watershed Area and Recharge		--	--

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the benthic nutrient flux Surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters within the Namskaket Marsh Estuarine System. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

As stated in above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the Namskaket Salt Marsh System predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton "particles". Most of these "particles" remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like 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. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with their associated nitrogen "load" become incorporated into the surficial sediments of the bays.

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

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment 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 deep depositional basins or salt marsh tidal creeks like Namskaket Marsh, 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). These latter salt marsh channels typify the estuarine system under consideration in this

threshold report, which is essentially tidal salt marsh with a dominant central creek, smaller tributary creeks and a salt marsh plain colonized mainly by low and high salt marsh plants.

Failure to account for the nitrogen balance of the sediments generally results in significant errors in determination of threshold nitrogen loadings. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for determining sediment-watercolumn nitrogen exchange

For the Namskaket Salt Marsh System, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected from 8 sites along the tidal salt marsh creek (Figure IV-8) 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-8) per incubation are as follows:

Namskaket Marsh Benthic Nutrient Regeneration Cores
- Station NAM-1   1 core   (Upper Creek)
- Station NAM-2   1 core   (Upper Creek)
- Station NAM-3   1 core   (Upper Creek)
- Station NAM-4   1 core   (Upper Creek)
- Station NAM-5   1 core   (Upper Creek)
- Station NAM-6   1 core   (Lower Creek)
- Station NAM-7   1 core   (Lower Creek)
- Station NAM-8   1 core   (Lower Creek, Mouth)

Sampling was distributed throughout the primary tidal reach of this system and the results for each site combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

Sediment-water column exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1998) for nutrients and metabolism. Upon return to the field laboratory (Harbormasters 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°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.
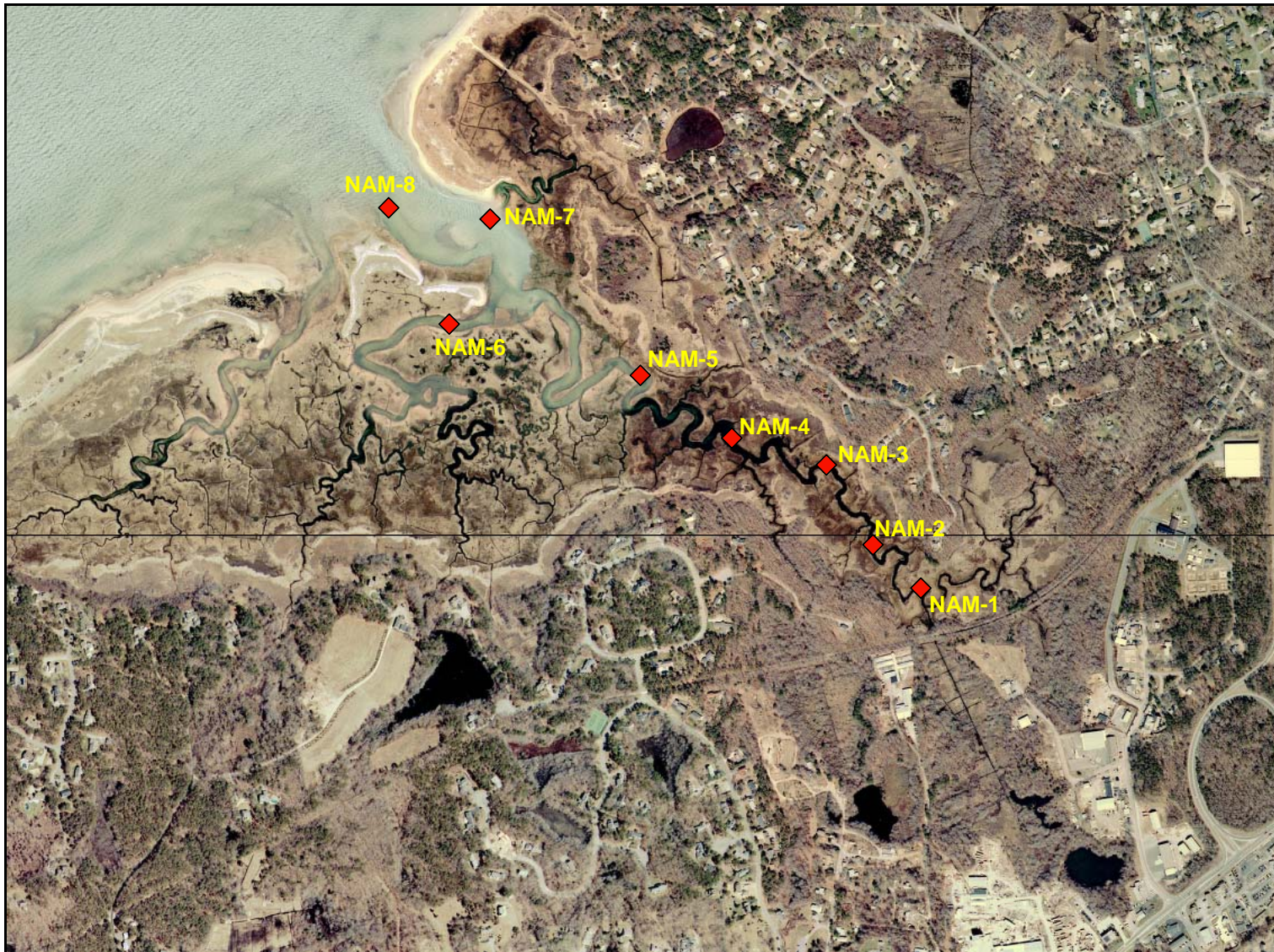
Figure IV-8.   Namskaket Marsh embayment system sediment sampling sites (red symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above.

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.

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-9).
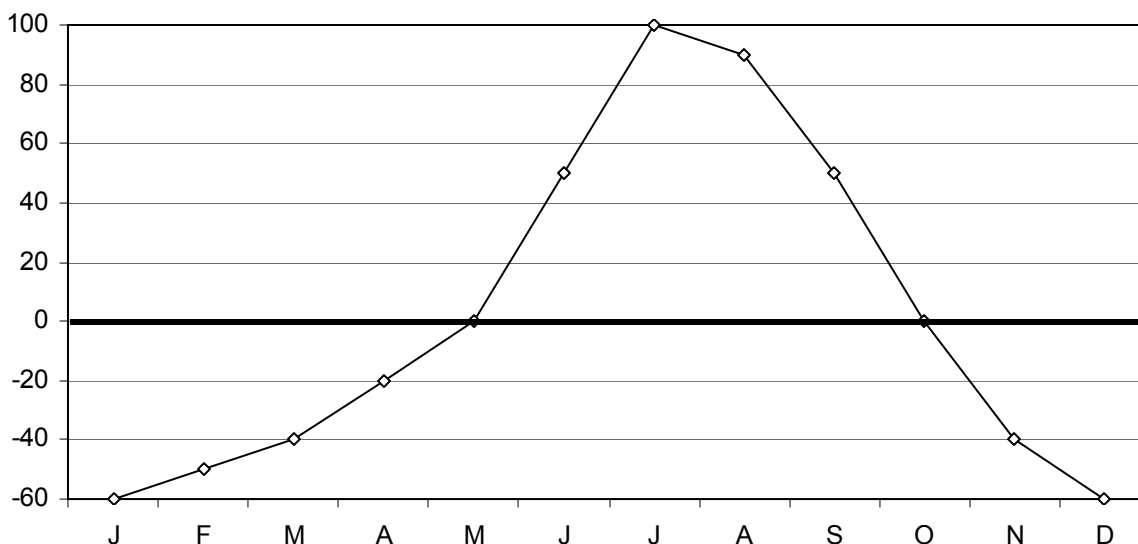
Figure IV-9.   Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

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

Sediment sampling was conducted throughout the Namskaket salt marsh tidal creek in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

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

Net nitrogen release or uptake from the sediments within the Namskaket Estuarine System were comparable to other similar salt marsh dominated systems with similar configuration and flushing rates. The spatial distribution of nitrogen release/uptake by the sediments of Namskaket Marsh was similar to adjacent Little Namskaket Marsh, with release of nitrogen in the smaller tidal creek areas of the upper marsh, 45.4 vs 64.5 mg N m^{-2} d^{-1}, respectively and uptake in the lower larger creek areas of -21.2 vs -7.8 mg N m^{-2} d^{-1}, respectively. In general, Namskaket Marsh showed slightly lower release rates (both less positive and more negative) than Little Namskaket Marsh, possibly related to their differences in tidal creek length or marsh "size", as they both presently have similar rates of watershed N loading. In contrast, within the Rock Harbor System nitrogen uptake was found in the overall upper salt marsh reach, which may relate to an effective shifting of the beginning of the tidal creek to the head of the lower dredged basin. Overall, the rates of uptake and release in the salt marsh dominated areas of these three adjacent systems are similar.

The salt marsh rates of uptake were also similar to other salt marsh systems on Cape Cod. For example, net nitrogen uptake in the salt marsh creek (-7.8 mg N m^{-1} d^{-1}) was similar to that observed for the salt marsh areas in the Centerville River System (-4.5 to -13.2 mg N m^{-1} d^{-1}) and Cockle Cove Salt Marsh, Chatham (MEP Centerville River Final Nutrient Technical Report 2006, MEP Cockle Cove Technical Memorandum-Howes et al. 2006).

Net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the Namskaket Salt Marsh System (Chapter VI) are presented in Table IV-6. There was a clear spatial pattern of sediment nitrogen flux, with net release from the sediments of the upper reach of the tidal creek and net uptake by the sediments of the lower tidal creek region. The sediments within the Namskaket System showed nitrogen fluxes typical of similarly structured systems with low to moderate watershed nitrogen loading and appear to be in

balance with the overlying waters and the nitrogen flux rates consistent with the low nitrogen loading to this system and it relatively high flushing rate.

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

| Location | Sediment Nitrogen Flux (mg N m^{-2} d^{-1}) | | | i.d. * |
	Mean	S.E.	# sites	
Namskaket Marsh System				
Upper Salt Marsh Creek	45.4	26.7	5	NAM 1 – 5
Lower Salt Marsh Creek	-21.2	4.1	3	NAM 6 - 8
* Station numbers refer to Figures IV-8.				

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

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

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

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

A hydrodynamic study was performed for the Namskaket Creek system. A section of a topographic map in Figure V-1 shows the general study area. The entire Namskaket Creek system has a surface coverage of 150 acres, and is comprised of marsh plain and marsh creeks. Circulation in the Namskaket Creek system is dominated by tidal exchange with Cape Cod Bay. The Harbor is connected to the Bay through a 430-foot wide main inlet, and a 200-foot-wide secondary inlet, both which empty onto a broad tidal flat over Skaket Beach.

This hydrodynamic study proceeded as two component efforts. In the first portion of the study, bathymetry, tide, and circulation velocity data were collected in order to accurately characterize the physical system, and to provide data necessary for the modeling portion of the study. The bathymetry survey of Namskaket Creek was performed to determine the present variation of the main Harbor basin and channel depths throughout the system. These tide data were necessary to run and calibrate the hydrodynamic model of the system.

Figure V-1.   Topographic map detail of the Cape Cod Bay embayments of Orleans, Massachusetts, including Namskaket Creek.

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

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

V.2 DATA COLLECTION AND ANALYSIS

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

V.2.1 Bathymetry Data Collection

Bathymetric data were collected in the Orleans salt water embayments, as part of a larger town-wide effort, over the course of six separate surveys, occurring between October 30 and December 11, 2001. The surveys employed an Odem HydroTrac fathometer mounted on a 16 ft motor 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. Marsh channels in the upper portion of the marsh areas were also surveyed, where depths allowed the passage of the survey boat. The actual survey paths are shown in Figure V-2, for surveys that were completed during this project. Collected bathymetry data will be tide-corrected, to account for the change in water depths as the tide level changes. The tide-correction is performed using tide data collected while the survey was run.

Figure V-2.   Actual paths followed by recent (Fall, 2001) survey boat during bathymetry surveys of the Cape Cod Bay embayments of Orleans, MA. Fathometer paths are plotted on a composite 1994 aerial photograph of the area.

Marsh plain topography data on the marsh plane were also collected in these systems using a level and stadia rod. The topography data were necessary to set the elevation of the marsh plain included in the hydrodynamic model.

V.2.2 Tide Data Collection and Analysis

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

The instruments deployed in this study were typically 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 in the 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).

The deployment locations for all the Orleans Cape Cod Bay embayment gages are shown in Figure V-3. Tides were measured offshore, at a location in the vicinity of the "target ship", and at stations inside each of the three Orleans Cape Cod Bay embayments systems, in Rock Harbor, Little Namskaket Creek, and Namskaket Creek. The total Cape Cod Bay deployment spanned early November to early January. For comparison, the complete tide data record is plotted in Figure V-4, from each gage deployed in the Orleans Cape Cod Bay embayments study.
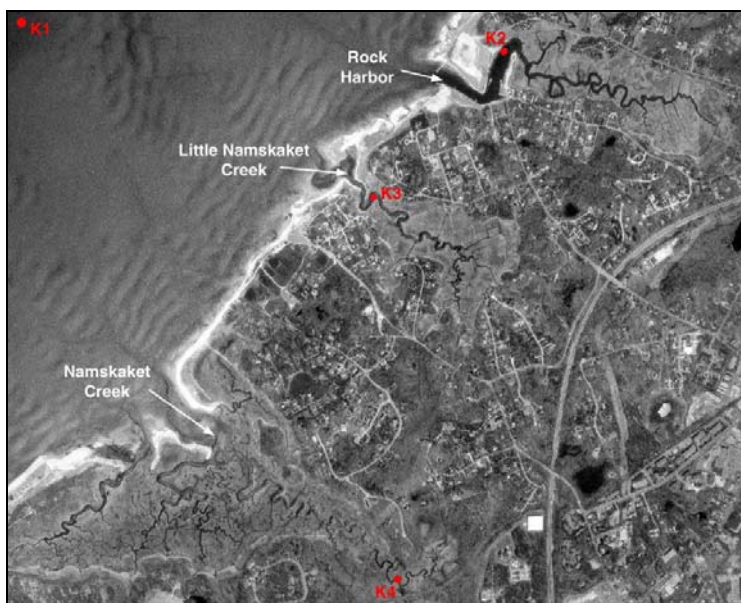
Figure V-3.   Tide gage locations for the three Cape Cod Bay embayments of Orleans, at Rock Harbor (K2), Little Namskaket Creek (K3), and Namskaket Creek (K4).

An harmonic analysis was performed on the time series 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 the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-5.
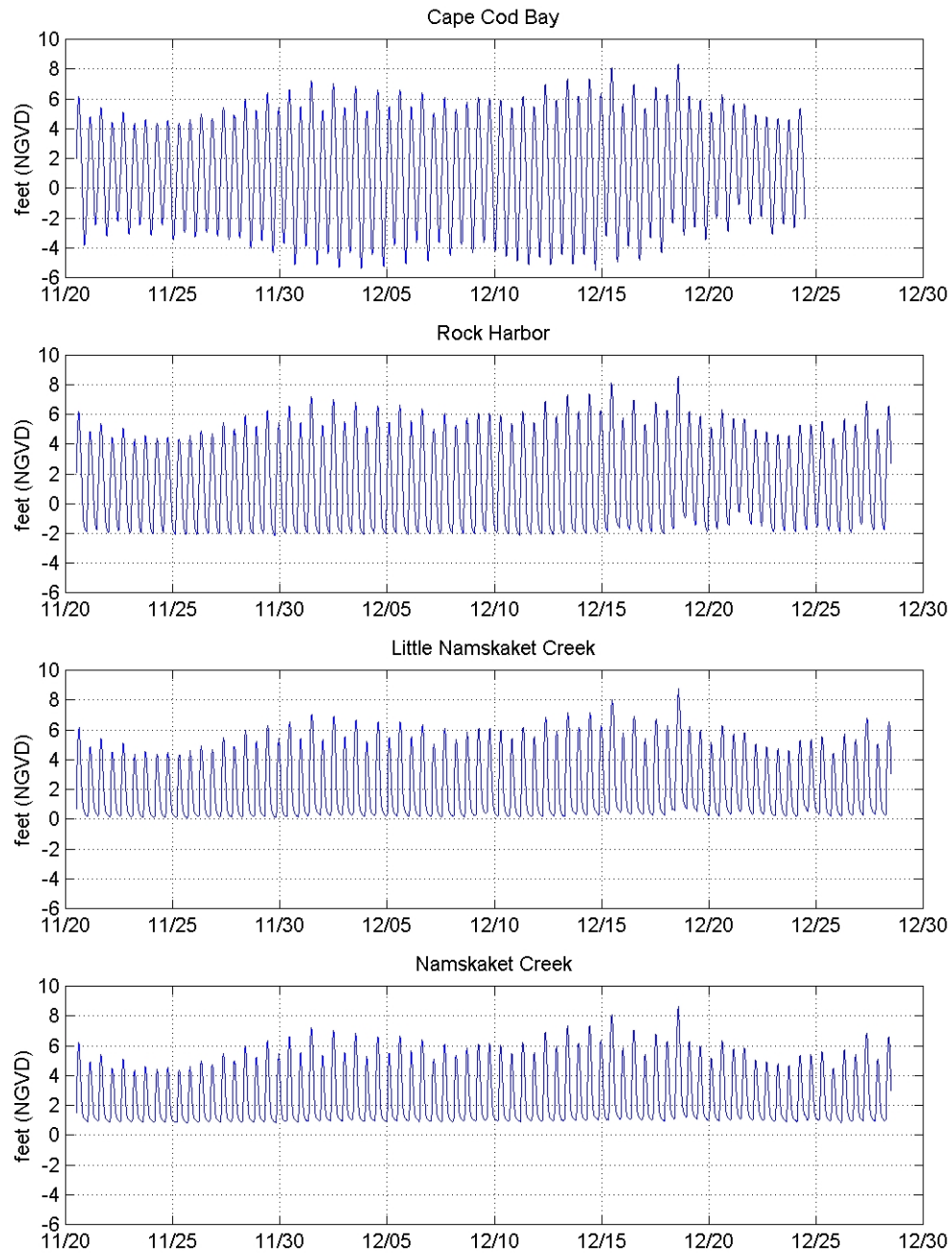
Figure V-4.   Complete TDR records for gages deployed for the Cape Cod Bay embayments of Orleans during late 2001.

Table V-1.	Major tidal constituents determined for gauge locations in the Cape Cod Bay embayments of Orleans, for the time period November 20 through December 24, 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
Cape Cod Bay	4.58	0.09	0.22	0.69	0.84	0.64	0.41	0.19
Rock Harbor	3.82	0.50	0.48	0.48	0.58	0.50	0.34	0.24
Little Namskaket Creek	2.31	0.91	0.17	0.34	0.36	0.38	0.30	0.31
Namskaket Creek	2.67	0.92	0.18	0.37	0.42	0.44	0.33	0.33
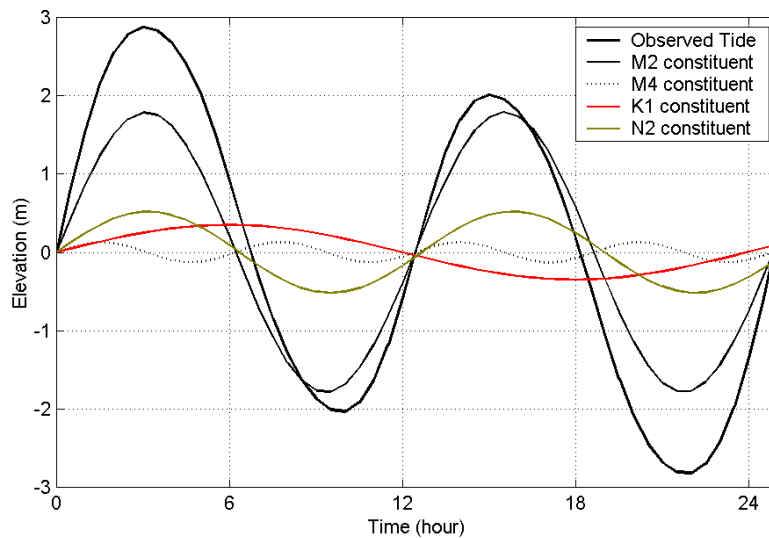
Figure V-5.   Example of an observed astronomical tide as the sum of its primary constituents.

Table V-1 presents the amplitudes of eight tidal constituents in the three Orleans Cape Cod Bay embayment systems. 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., 4.6 feet for the tide offshore in Cape Cod Bay. The K_1 and O_1 constituents represent diurnal tides that occur once daily, associated with the sun and moon respectively.

Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, contribute significantly to the total tide signal, with amplitudes that are typically each about 10% of the total observed tide. The M_{sf} is a lunarsolar fortnightly constituent with a period of approximately 14 days, and is the result of the periodic conjunction of the sun and moon. 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.

Data in Table V-1 show how the constituents vary as the tide propagates into the upper reaches of these marsh systems. Note the reduction in the M_2 amplitude between Cape Cod Bay and the main basin of Rock Harbor, and farther up into the marsh of Namskaket and Little Namskaket creeks. The main M_2 and K_1 tidal constituents are smaller inside the marshes due to truncation of the lower portion of the tide. This truncation occurs because the channel bottoms in each system are high enough to limit the lower range of the tide. This effect is also

apparent in Figure V-6. Frictional damping also is evident by the harmonic constituents, where drag on the channel sides and bottom causes some energy transfer from the M_2 to the higher order M_4 and M_6. This is seen by how the M_4 and M_6 increase in amplitude inside the systems, compared the constituents calculated for the Cape Cod Bay station.

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 embayment systems of Orleans 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 Nauset Harbor, with the computed astronomical (predicted) tide resulting from the harmonic analysis, and the resulting non-tidal residual signal.

Table V-2 shows that the variance of tidal energy was largest in the data record from Cape Cod Bay for all the deployed gauges; as should be expected since the tide range is the greatest at this location, compared to the other sites. In general, the energy of the signal decreases with distance from the offshore gage, with the lowest energy found in upper regions of each system. The analysis also shows that tides are responsible for typically more than 90% of the water level changes in each system; wind effects in these data sets were negligible.

V.3 HYDRODYNAMIC MODELING

For the Namskaket Creek system, Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing. The particular computed 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 with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by a Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report primarily were generated within the SMS modeling package.
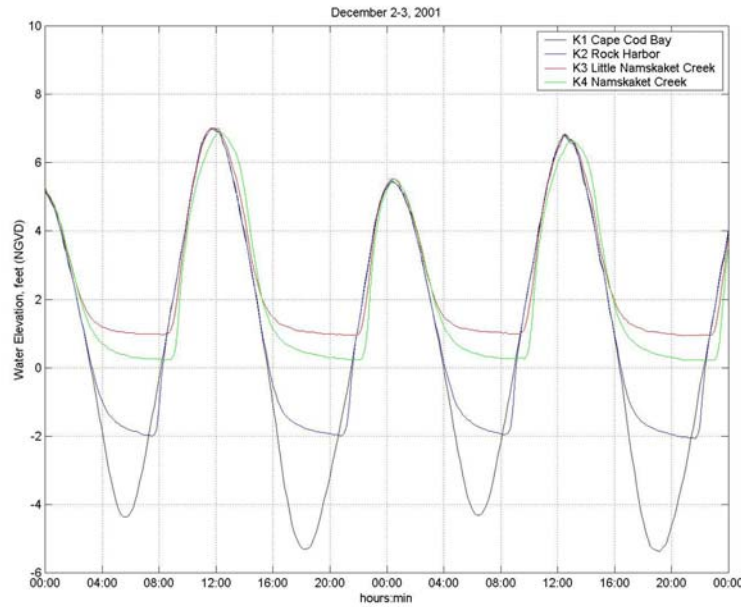
Figure V-6. Close-up of TDR record of tides recorded in Cape Cod Bay, and the three Orleans embayments connected to Cape Cod Bay. From this plot significant attenuation, is apparent caused by the influence of the extensive tidal flats that separate these systems from Cape Cod Bay at low tide.   This effect of the marsh is seen by how ebbing water levels do not fall below a certain level, as if a weir or sill was present to prevent water from dropping below this level, while having very little effect on the amplitude and phase of the flooding portion of the tide.

Table V-2. Percentages of Tidal versus Non-Tidal Energy for the Cape Cod Bay embayments of Orleans.			
TDR Location	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Cape Cod Bay	10.74	98.5	1.5
Rock Harbor	7.56	97.5	2.5
Little Namskaket Creek	3.22	95.4	4.6
Namskaket Creek	4.18	94.6	5.4

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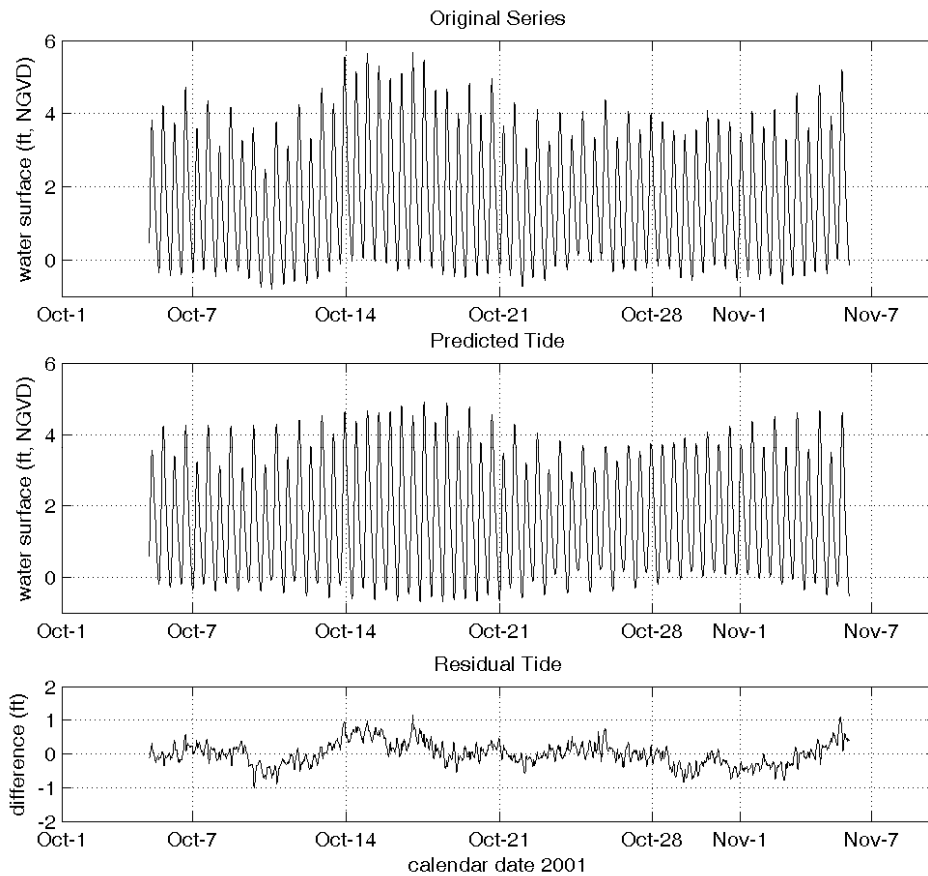
Figure V-7.   Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 23 individual tide constituents determine in the harmonic analysis of the Town Cove (sub-embayment of the Nauset Harbor system) gauge data.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

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 each of the five separate 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 each

system based on the tide gauge data collected offshore Skaket Beach Once the grid and boundary conditions were set, the model was calibrated to ensure that each 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 to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid Generation

The grid generation process was aided by the use of the SMS package. 1994 digital aerial orthophotos and recent bathymetry survey data were imported to SMS to facilitate the construction of finite element grids to represent each of the modeled estuaries. 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 mesh for the Namskaket Creek system is shown in Figure V-8. The Namskaket Creek grid has a total of 5343 nodes that make up 2191 quadrilateral elements. The maximum depth included in the model is -2.5 feet NGVD, near the mouth to Cape Cod Bay. Bathymetry data were interpolated to the developed finite element mesh of each system, as seen in Figure V-9. A typical marsh plain elevation of +5.0 ft NGVD was used, based on spot surveys of the marsh plain. This elevation also roughly corresponds to the mean high water (MHW) level in the marsh systems, which is typical.

The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties of the five modeled embayments. 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. Fine resolution was required to simulate channel constrictions that significantly impact the estuarine hydrodynamics, e.g. the Dyer Prence Road culvert, as well as marsh and tidal creeks found in the system. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the modeled estuaries.

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 harbor's main basin and on the upper reaches of the modeled marsh plains. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

V.3.2.2 Boundary condition specification

Two types of boundary conditions were employed for the RMA-2 model of Namskaket Creek: 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.
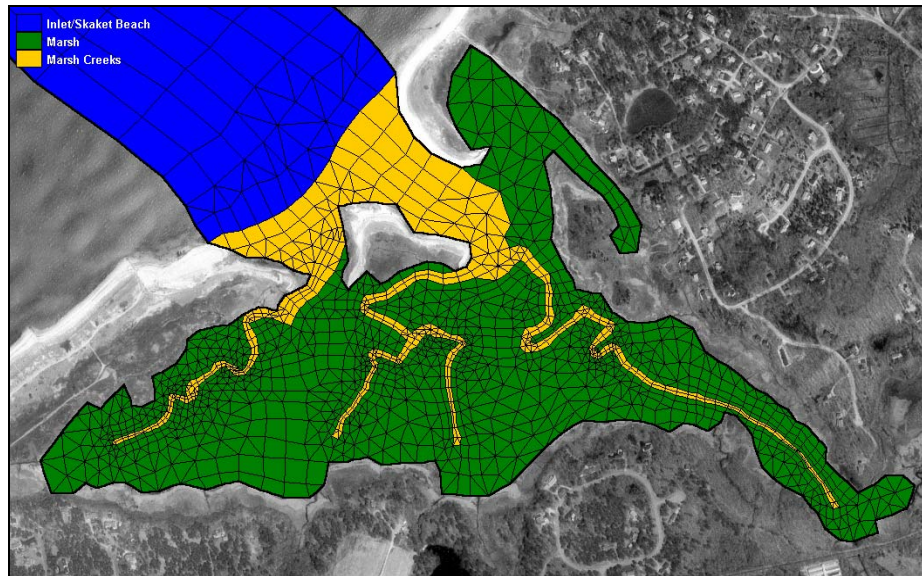
Figure V-8.   Plot of numerical grid used for hydrodynamic modeling of the Namskaket Creek system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates.
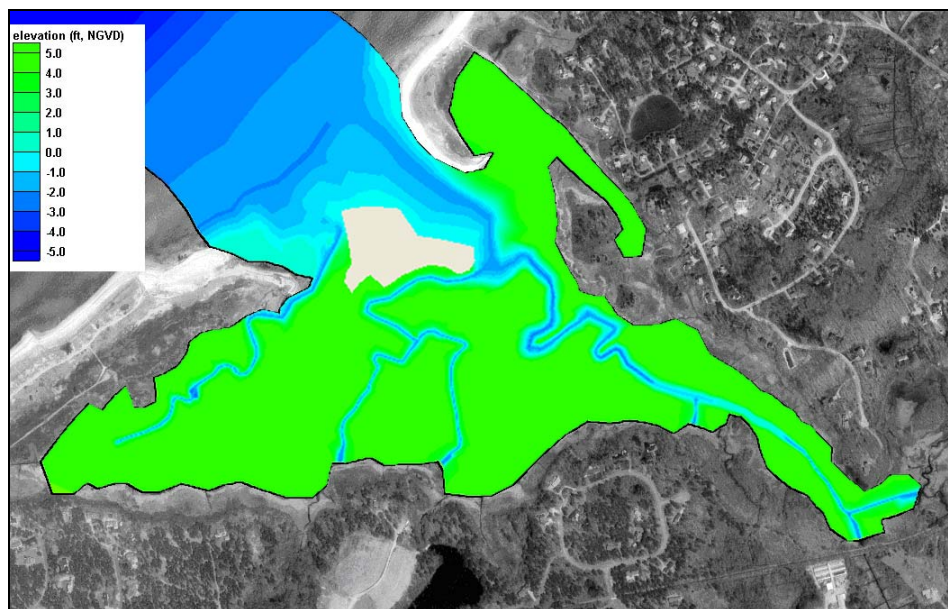
Figure V-9.   Depth contour plot of the numerical grid for Namskaket Creek showing 1-foot contour intervals relative to NGVD29.

A tidal boundary condition was specified at the inlet.   TDR measurement tide data collected offshore Skaket Beach provided the required data.   The rise and fall of the tide in Cape Cod Bay is the primary driving force for estuarine circulation in the modeled system. Dynamic (time-varying) model simulations specified a new water surface elevation at the model open boundary every model time step (10 minutes); therefore, the model time step selected for each system corresponded to the time step of the tide data record.

V.3.2.3 Calibration

After developing the finite element grid, and specifying boundary conditions, the Namskaket Creek model was calibrated. The calibration procedure ensures that the model predicts accurately what was observed in nature during the field measurement program. Numerous model simulations are required (typically 20+) for an estuary model, specifying a range of friction and eddy viscosity coefficients, to calibrate the model.

Calibration of the hydrodynamic model required a close match between the modeled and measured tides. 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, or 5 lunar days) was modeled to calibrate the model based on dominant tidal constituents discussed previously in the data collection section (Section W). For Namskaket Creek, the calibration period began November 30, 2001 at 1100 EST. 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

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 verification period for Namskaket Creek began December 7, 2001 at 1600 EST.

The calibrated model was 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 used for each system. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events.

V.3.2.3.1 Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a 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 the smooth sandy channel found in the lower portion of Namskaket Creek, versus the meandering marsh creek channels of the upper marsh, 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 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.

V.3.2.3.2 Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and 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, and in shallow inlets, to ensure numerical stability.

V.3.2.3.3 Marsh porosity processes

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 rises within the channels and creeks initially until water surface elevation reaches the marsh plain, when at this point the water level remains nearly constant as water 'fans' out over the marsh surface. The rapid flooding of the marsh surface corresponds to a flattening out of the tide curve approaching high water.

Marsh porosity is a feature of the RMA-2 model that permits the modeling of hydrodynamics in marshes. This model feature essentially simulates the store-and-release capability of the marsh plain by allowing grid elements to transition gradually between wet and dry states. This technique allows RMA-2 to change the ability of an element to hold water, like squeezing a sponge. 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 the four modeled Orleans embayments which include marsh resources.

Table V-3.	Manning's Roughness coefficients used in simulations of modeled embayments. These embayment delineations correspond to the material type areas shown in Figure V-8.	
System Embayment	**Bottom Friction**	
Namskaket Creek Inlet (beach)	0.150	
Namskaket Creek marsh plain	0.050	
Namskaket Creek marsh creeks	0.020	

V.3.2.3.4 Comparison of modeled tides and measured tide data

A best-fit of model predictions for the TDR deployments was achieved using the aforementioned values for friction and turbulent exchange. Figures V-10 V-11 illustrate the five-day calibration simulation along with 50-hour sub-section, for the Namskaket Creek model. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

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 report Table V-1 because constituents were computed for only the five-day section of the longer time periods 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.
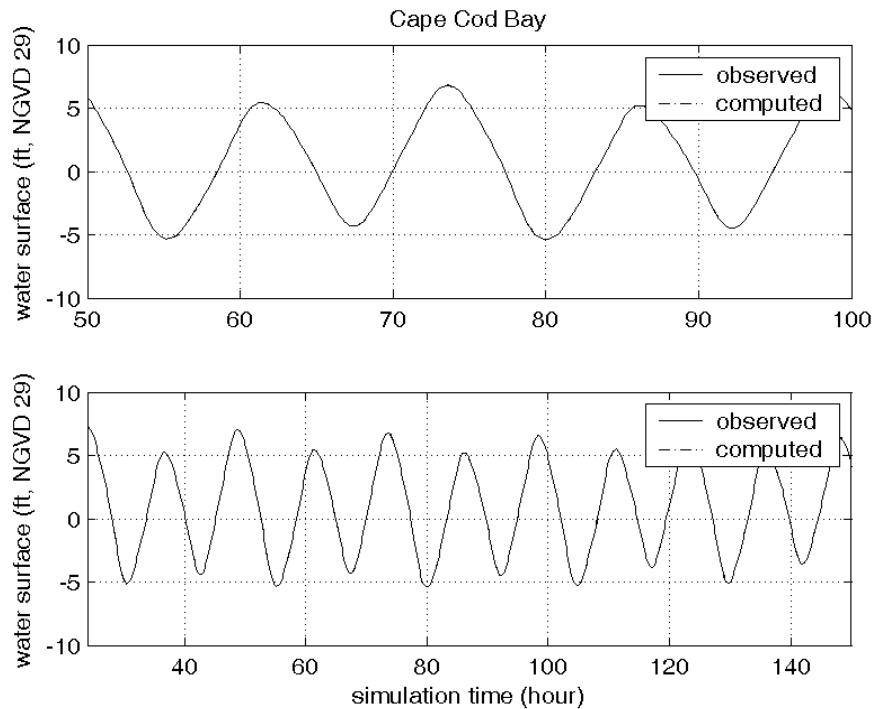
Figure V-10. Comparison of model output and measured tides for the TDR location offshore Skaket Beach (Cape Cod Bay), during model calibration time period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.
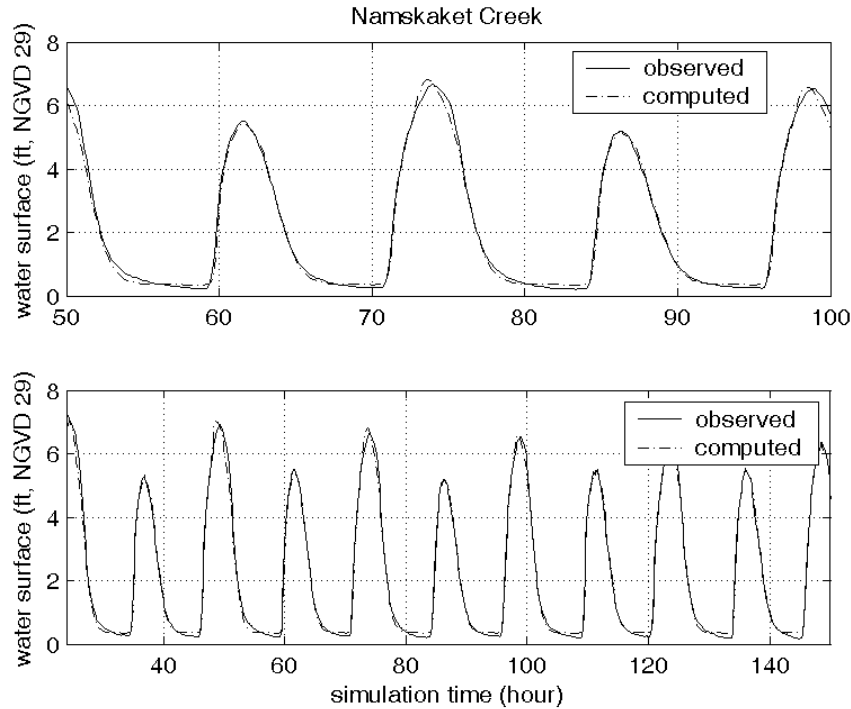
Figure V-11.   Comparison of model output and measured tides for the TDR location in Namskaket Creek, during model calibration time period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

Table V-4. Tidal constituents for measured water level data and calibrated model output for Namskaket Creek 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
Cape Cod Bay*[a]	5.14	0.12	0.28	0.98	10.6	185.3
Namskaket Creek	2.79	1.08	0.24	0.62	22.6	32.6
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay*[a]	5.14	0.12	0.28	0.98	10.6	184.1
Namskaket Creek	2.82	1.07	0.18	0.67	23.6	30.4
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay*[a]	0.00	0.00	0.00	0.00	0	-1
Namskaket Creek	0.03	-0.01	-0.06	0.05	2	-2

*model open boundary

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 gages (±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.

V.3.3 Model Verification

The calibration procedure used in the development of the finite-element model of Namskaket Marsh required a match between measured and modeled tides. An additional model verification model run was performed to verify the model performance during time periods different from the calibration time period. In this fashion, the calibrated model is tested to ensure its accuracy when run for any time period outside the calibration period. The selected verification time period was chosen so that it did not overlap with the original calibration period. The results of the model verification runs are shown in Table V-5. The analysis of the verification model run in this table shows that the model performs with a similar degree of accuracy to the calibration run.

Table V-5.	Tidal constituents for measured water level data and calibrated model output for Namskaket Creek during model verification time period.					
Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay*[a]	5.19	0.11	0.28	0.66	64.8	-33.7
Namskaket Creek	2.91	1.09	0.27	0.46	76.7	137.9
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay*[a]	5.19	0.11	0.28	0.66	64.9	-37.8
Namskaket Creek	2.93	1.02	0.21	0.51	78.3	136.2
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay*[a]	0.00	0.00	0.00	0.00	0	-4
Namskaket Creek	0.02	-0.07	-0.06	0.05	3	-2

*model open boundary

V.4 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through inlet of Namskaket Creek, the primary mechanism controlling estuarine water quality within these systems is tidal exchange. For example, a rising tide offshore Namskaket Creek 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.

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.

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 will be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The water quality modeling of Chapter VI provides this critical tool to evaluate the complex mechanisms governing estuarine water quality in Namskaket Creek.

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 Namskaket Creek. 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 system are shown in Figure V-8 of the previous section. The RMA-2 model calculated flow

crossing specified grid lines for each sub-embayment, and this flow data was 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 volume and average tidal prism during simulation period.		
Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Cape Cod Bay Embayments		
Namskaket Creek System	10,286,900	19,799,000

Table V-7. Computed System and Local residence times for Namskaket Creek.	
Embayment	System Residence Time (days)
Namskaket Creek System	0.3

The computed flushing rates for Namskaket Creek show that the system generally flushes well, with flushing times less than a day for the whole system. Marsh systems like Namskaket Creek are expected to flush very well, since in marshes, the mean volume is much smaller than mean tidal prism.

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 all of the modeled Orleans embayments. Generally, possible errors in computed residence times could 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 in Cape Cod Bay is typically is strong, the "strong littoral drift" assumption is completely appropriate, and would result in only minor errors in residence time calculations.

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

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

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the system were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated hydrodynamic model representing the transport of water within the Namskaket Creek system. Files of node locations and node connectivity for the RMA-2 model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic output for the water quality model calibration was the 7 day period beginning October 24, 2001 1830 EST. This period corresponds to that used in the flushing analysis presented in Chapter V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model had reached a dynamic "steady state", and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

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

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. The multi-year averages present the "best" comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. Typically, six years of data (collected between 2001 and 2006) were available for stations monitored by SMAST.

Table VI-1. Measured data and modeled nitrogen concentrations for the Namskaket Marsh estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average all samples. Data represented in this table were collected in the summers of 2001 through 2006, except the Cape Cod Bay station, which are from the 2003 through 2005 seasons.

Sub-Embayment	monitoring station	data mean	s.d. all data	N	model min	model max	model average	model target
Namskaket - mouth	WMO-22	0.529	0.132	30	0.359	0.558	0.421	0.529
Namskaket - lower	WMO-23	0.658	0.209	18	0.362	0.737	0.488	0.658
Namskaket - upper	WMO-24	0.836	0.122	17	0.473	0.858	0.662	0.836
Cape Cod Bay	WMO-14	0.357	0.059	15	0.357	0.357	0.357	0.357

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

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 Namskaket Creek estuarine system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of Namskaket Creek. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod embayments, including systems other systems in Falmouth (Howes *et al.*, 2005); Mashpee, MA (Howes *et al.*, 2004) and Chatham, MA (Howes *et al.*, 2003).

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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 Namskaket Creek system.

VI.2.1 Model Formulation

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

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

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

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

The RMA-4 model can be utilized to predict both spatial and temporal variations in total for a given embayment system. At each time step, the model computes constituent concentrations over the entire finite element grid and utilizes a continuity of mass equation to check these results. Similar to the hydrodynamic model, the water quality model evaluates model parameters at every element at 10-minute time intervals throughout the grid system. For this application, the RMA-4 model was used to predict tidally averaged total nitrogen concentrations throughout the sub-embayments of the Namskaket Creek 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 Namskaket Creek also 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 the freshwater portion of Namskaket Creek (1.84 ft^3/sec).

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

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the results of the watershed analysis with nitrogen attenuation rates determined from the surface water measurements, 2) estimates of direct atmospheric deposition, 3) summer benthic regeneration, and 4) the point source input developed from measurements of the discharge of the freshwater portion of Namskaket Creek.   Nitrogen loads from the marsh's watersheds were distributed along the length of the system. Loads from the watershed were applied at elements within the marsh creeks represented in the model. Benthic regeneration loads were distributed among another sub-set of grid cells in the marsh creeks.

The loadings used to model present conditions in the Namskaket Creek system are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Present conditions include the measured load discharged by Namskaket Stream. As there is no evidence that the plume of treated effluent from the Tri-Town Septage Treatment Facility was discharging to the Namskaket Estuary at the time of the MEP analysis, this load was not included under present loading in Table VI-2. It was considered in Scenario analysis in presented in chapters below. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the creek channel surface area coverage (excluding the marsh plain) representing each separate core, resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. Benthic flux loads can be positive or negative. In Namskaket Creek, the sum of all benthic flux in the system is negative, indicating that on average the bottom sediments of the creek channels and harbor basin are a net nitrogen sink.

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 Cape Cod region offshore the entrance to the Creek was set at 0.357 mg/L, based on SMAST data collected in the summers of 2003 through 2005.

VI.2.4 Model Calibration

Calibration of the total nitrogen model of Namskaket Creek proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (*E*) values were varied through the modeled system by

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

Table VI-2.	Sub-embayment and surface water loads used for total nitrogen modeling of the Namskaket Creek system, with total watershed N loads[1], atmospheric N loads, and benthic flux. These loads represent **present loading conditions** for the listed sub-embayments.		
sub-embayment	watershed load[1] (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Namskaket marsh	9.290	0.118	-0.409
Namskaket Creek (freshwater)	3.395	-	-
System Total	12.685	0.118	-0.409
[1] does not include discharge from the Tri-Town Septage Treatment Facility			

Table VI-3.	Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for the Namskaket Creek estuary system.
Embayment Division	E m^2/sec
Open Boundary - Cape Cod Bay	10.0
Marsh channels	10.0
marsh plain	10.0
Namskaket Creek discharge	1.0

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

For model calibration, the mid-point between maximum modeled TN and average modeled TN was compared to mean measured TN data values, at water-quality monitoring stations WMO-22 and WMO-23. The calibration target would fall between the modeled mean and maximum TN because the of the timing that the measurements are typically taken during the tide cycle (mid-ebb), and because the stations are located in shallow marsh creeks. For station WMO-24, the maximum modeled concentration was selected as the model target, because the measurements taken at this far-upstream station are taken when the marsh creek

is nearly dry, and N concentrations are at their highest during the tide cycle. Also presented in this figure are unity plot comparisons of measured data verses modeled target values for each system.
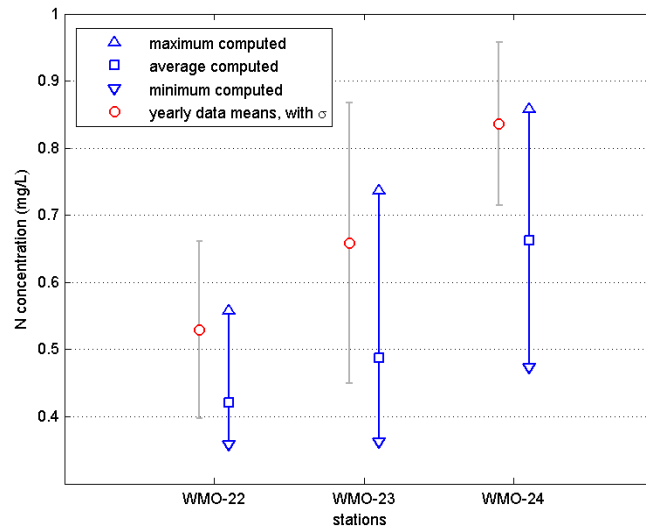
Figure VI-2.   Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Namskaket Creek system. Station labels correspond with those provided in Table VI-1.   Model output is presented as a range of values from minimum to maximum values computed during the simulation 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

Figure VI-3.   Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) are 0.91 and 0.04 mg/L, respectively.

A contour plot of calibrated model output is shown in Figures VI-4. In this figure, color contours indicate nitrogen concentrations throughout the model domain. The output in these

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figures show average total nitrogen concentrations, computed using the full 7-tidal-day model simulation output period.
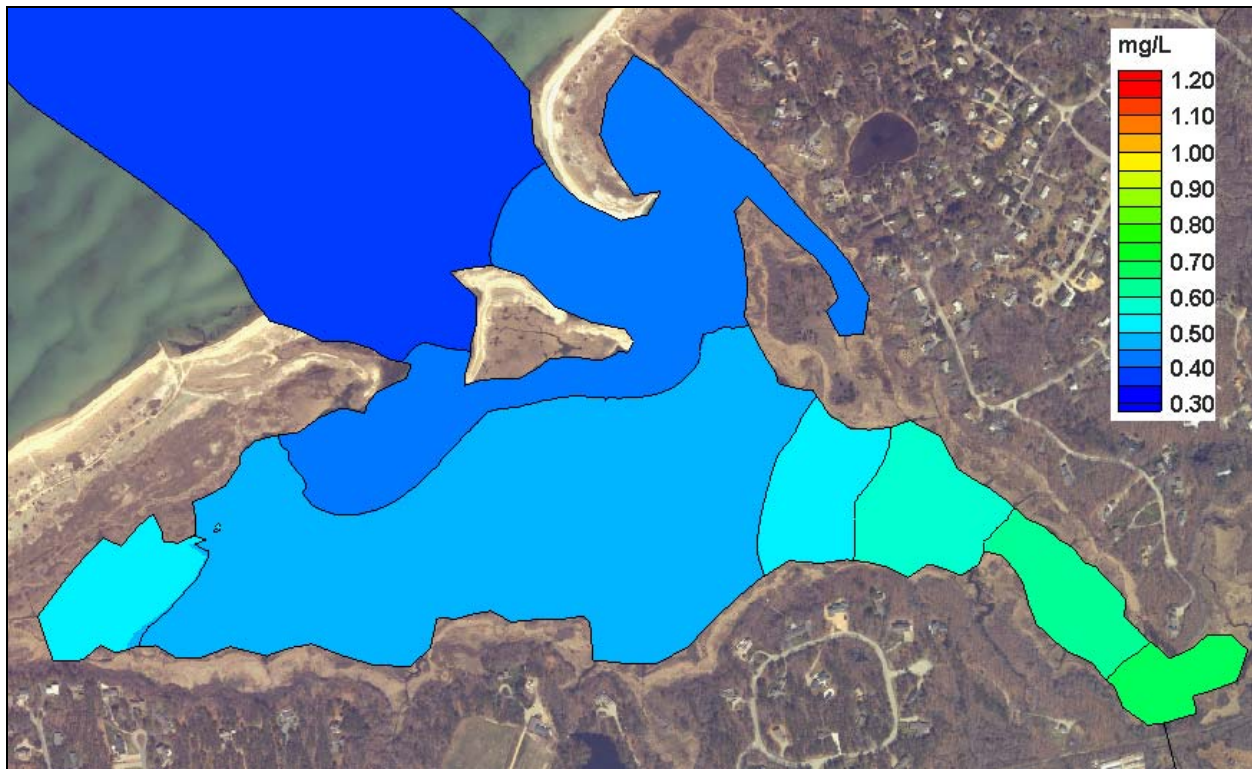
Figure VI-4.   Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Namskaket Creek system.

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 Namskaket Creek system using salinity data collected at the same stations as the nitrogen data. The only required inputs into the RMA4 salinity model of each system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, at the freshwater stream discharges, and groundwater inputs. The open boundary salinity was set at 30.8 ppt. For surface water steams and groundwater inputs salinities were set at 0 ppt. Surface water stream flow rates for the streams were the same as those used for the total nitrogen model, as presented earlier in this section. The groundwater inputs used for the system was 5.18 ft^3/sec (12,660 m^3/day). Groundwater flows were distributed evenly in the model through the use of 1-D element input points positioned along each model's land boundary.

Comparisons of modeled and measured salinities are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients throughout the Namskaket Creek estuary system. The rms error of the model is less than 5 ppt, and correlation coefficient between the model and measured salinity data is 0.83.   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.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the Namskaket Creek, 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-embayment, as well as a natural forest within each watershed. Comparisons of the alternate watershed loading analyses are shown in Table VI-4. Loads are presented in kilograms per day (kg/day) in this Section, since it is inappropriate to show benthic flux loads in kilograms per year due to seasonal variability.
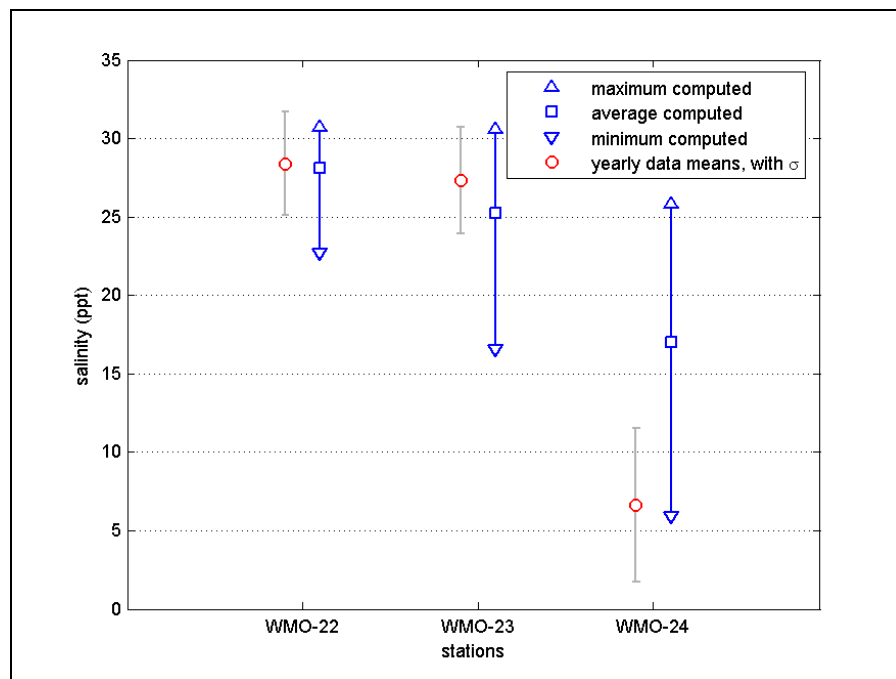
Figure VI-5.   Comparison of measured and calibrated model output at stations in Namskaket Creek. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset.
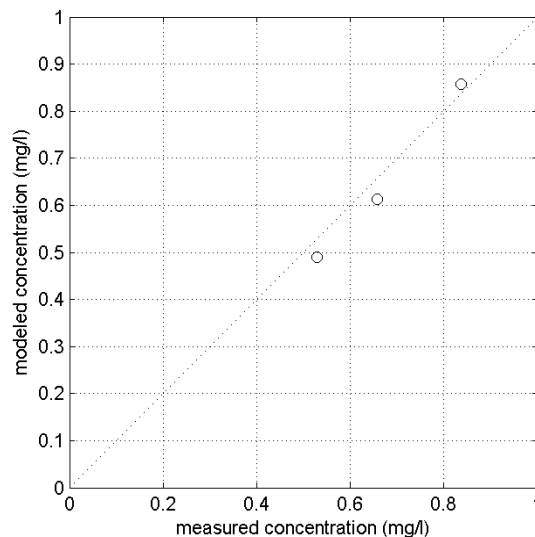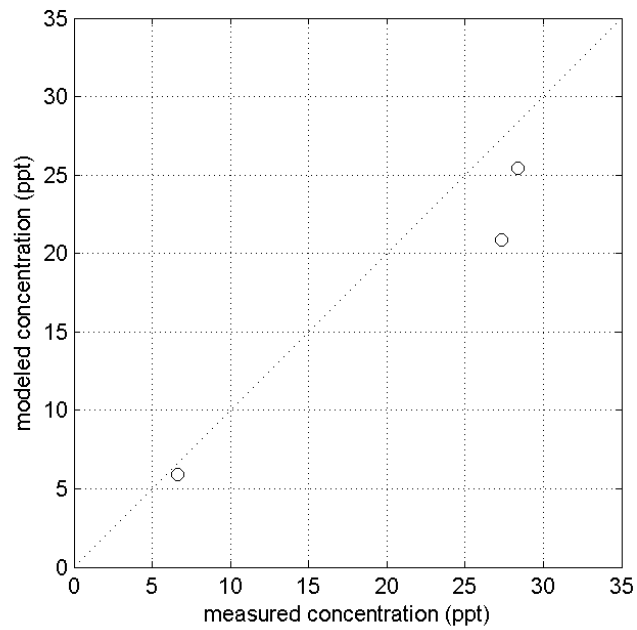
Figure VI-6.   Model salinity target values are plotted against measured concentrations, together with the unity line.   Computed correlation (R^2) and error (rms) are 0.83 and 4.1 ppt, respectively
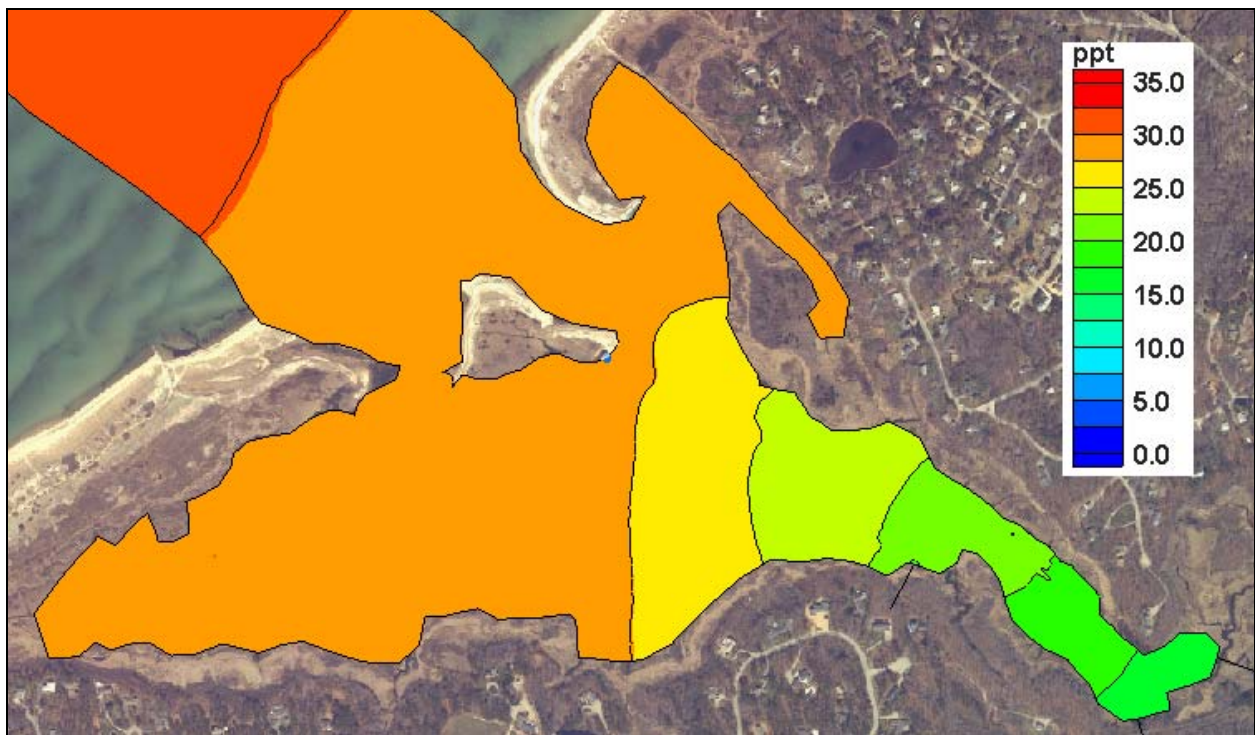
Figure VI-7.   Contour Plot of modeled salinity (ppt) in Namskaket Creek system.

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 Namskaket Creek 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
Namskaket marsh	9.290	11.205	+20.6%	5.334	-42.6%
Namskaket Creek (freshwater)	3.395	14.381	+323.6%	0.800	-76.4%
System Total	12.685	25.586	+101.7%	6.134	-51.6%

VI.2.6.1 Build-Out

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

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Table VI-5.	**Build-out** sub-embayment and surface water loads used for total nitrogen modeling of the Namskaket Creek 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)
Namskaket marsh	11.205	0.118	-0.373
Namskaket Creek (freshwater)	14.381	-	-
System Total	25.586	0.118	-0.373
*does not include N discharged by the Tri Town Facility			

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model was run to determine nitrogen concentrations across the system (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Cape Cod Bay) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most in the upper portions of the system, with the largest change at the Namskaket Creek freshwater discharge (+176.3% at WMO-24), with the least change occurring in the creek mouth (29.1% at WMO-22) near the system's inlet to Cape Cod Bay.

Color contours of model output for the build-out scenario are present in Figure VI-8. 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.

Table VI-6.	Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Namskaket Creek system. The sentinel threshold station is in bold print.			
Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Namskaket - mouth	WMO-22	0.421	0.543	+29.1%
Namskaket - lower	**WMO-23**	**0.488**	**0.778**	**+59.7%**
Namskaket - upper	WMO-24	0.662	1.830	+176.3%
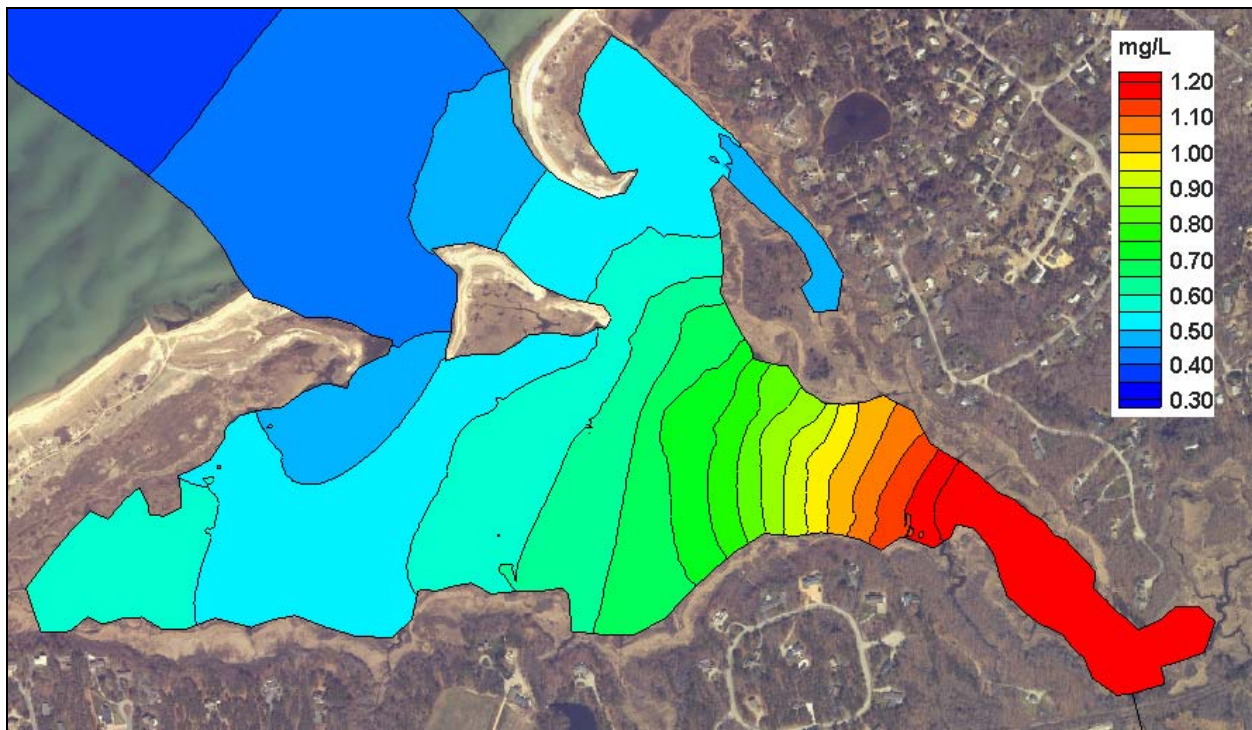
Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Namskaket Creek system, for projected build-out loading conditions.

VI.2.6.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering each sub-embayment for the no anthropogenic load ("no load") scenarios is shown in Table VI-7. The benthic flux input to each embayment was reduced (toward zero) based on the reduction in the watershed load (as discussed in §VI.2.6.1). Compared to the modeled present conditions and build-out scenario, atmospheric deposition directly to each sub-embayment becomes a greater percentage of the total nitrogen load as the watershed load and related benthic flux decrease.

Table VI-7.	"**No anthropogenic loading**" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Namskaket Creek 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)
Namskaket marsh	5.334	0.118	-0.427
Namskaket Creek (freshwater)	0.800	-	-
System Total	6.134	0.118	-0.427

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations across the system. Again, total nitrogen concentrations in the receiving waters (i.e., Cape Cod Bay) 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 greater than 47% (at WMO-24) occurring the upper portions of the system. Results for the system are shown pictorially in Figure VI-9.

| 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 Namskaket Creek system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The sentinel threshold station is in bold print.			
Sub-Embayment	monitoring station	present (mg/L)	no load (mg/L)	% change
Namskaket - mouth	WMO-22	0.421	0.376	-10.7%
Namskaket - lower	**WMO-23**	**0.488**	**0.392**	**-19.7%**
Namskaket - upper	WMO-24	0.662	0.348	-47.4%
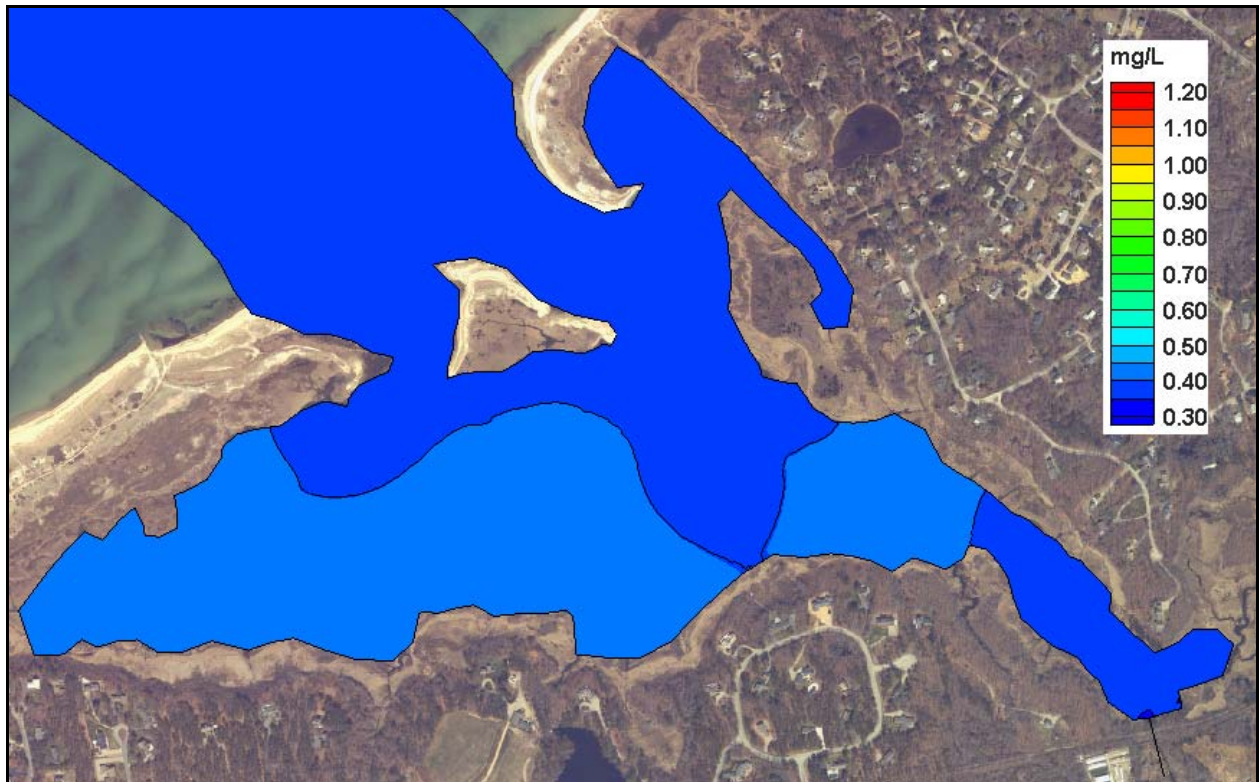
Figure VI-9.   Contour plot of modeled total nitrogen concentrations (mg/L) in Namskaket Creek, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Namskaket Marsh Estuarine System in the Towns of Orleans and Brewster, MA, our assessment is based upon data from the water quality monitoring database developed by the Town of Orleans Water Quality Monitoring Program and surveys of eelgrass distribution, benthic animal communities 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 this system (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen thresholds determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll a (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed dissolved oxygen sensors within the middle to lower portion of the main channel of the Namskaket Marsh system to record the frequency and duration of low oxygen conditions during the critical summer period. This location was selected as it would not go dry at low tide and was most likely to function as an embayment rather that a marsh tidal creek. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Namskaket Marsh 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.

In areas that do not support eelgrass beds, benthic animal indicators were used to assess the level of habitat health from "healthy" (low organic matter loading, high D.O.) to "highly stressed" (high organic matter loading-low D.O.). The basic concept is that certain species or

species assemblages reflect the quality of their habitat. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life-history information on the species and a wide variety of field studies within southeastern Massachusetts waters, including the Wild Harbor oil spill, benthic population studies in Buzzards Bay (Woods Hole Oceanographic Institution) and New Bedford (SMAST), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H') and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 3.8 mg L^{-1}. Massachusetts State Water Quality Classification indicates that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Namskaket Creek 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 (see Figure VII-1 for example). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, an autonomously recording oxygen sensor was moored 30 cm above the embayment bottom within the key region of the Namskaket Creek (Figure VII-2) system. The instruments was placed at the upper margin of the lower reach of the central tidal creek to this extensive salt marsh system. This lower region of the creek is the transition between the smaller upper marsh creek system and the offshore open waters. The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition, periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the Namskaket Marsh Estuary was collected during the summer of 2003.

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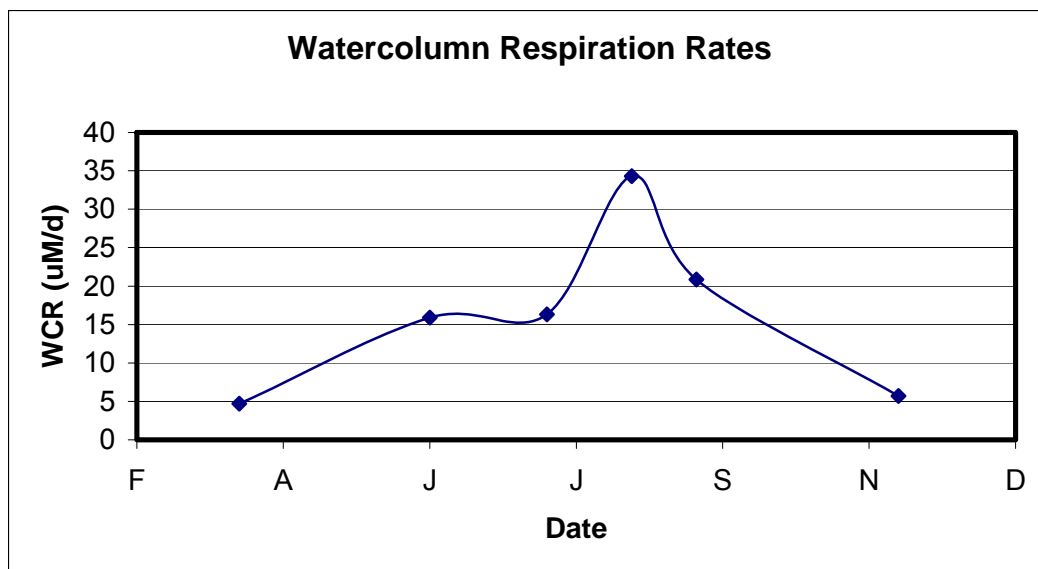
Figure VII-1.   By example, average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Namskaket Marsh system evaluated in this assessment showed high frequency variation, apparently related to diurnal and sometimes tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. 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.

Dissolved oxygen and chlorophyll a records were examined both for temporal trends and to determine the percent of the 25-28 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions. The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate organic and nutrient enriched tidal creek system associated with the mooring site within Namskaket Creek (Figures VII-3 and VII-4). The oxygen data is consistent with high organic matter loads from phytoplankton production (chlorophyll a levels) and organic matter inputs from the surrounding vegetated marsh. Both the levels of oxygen depletion and chlorophyll levels (frequently >10 ug/L) are indicative of a nitrogen and organic matter rich system. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in a particular location. However, nitrogen enrichment also results in increased phytoplankton (or epibenthic algae) production, as evidenced by oxygen levels that rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The absence of elevated oxygen levels is consistent with the oxygen variations being the response to the naturally organic rich nature of tidal salt marsh creeks. In these systems the oxygen dynamic is driven by consumption within

the tidal creeks, with re-oxygenation through phytoplankton production being limited. As the creeks drain nearly completely at low tide and the rise in oxygen levels is primarily through the entry of oxygen rich coastal waters on the flooding tide.

The dissolved oxygen records indicate that the upper region of the central tidal salt marsh creek of the extensive Namskaket salt marsh system has periodic oxygen depletion to 2 mg L^{-1} (Table VII-1). Such oxygen depletion is typical of organic and nutrient rich estuarine systems and in embayments indicates impaired habitat quality. In contrast, salt marshes are nutrient and organic matter enriched as part of their ecological design, which makes them such important nursery areas for adjacent offshore waters. However, a natural consequence of their organic rich sediments is periodic oxygen depletion within the tidal creeks, particularly during the summer. The observed level of oxygen depletion in Namskaket Creek is expected, as was the nearly identical pattern recorded in adjacent Little Namskaket Creek by the MEP Technical Team. Assessment of habitat quality must necessarily consider the natural function and tolerances of the specific estuarine ecosystems being evaluated. The specific results are as follows:

Namskaket Creek (Figures VII-3 and VII-4):

Namskaket Marsh functions primarily as a tidal salt marsh throughout its estuarine reach. The upper reach has deeply incised narrow creeks surrounded by extensive emergent marsh vegetated with typical New England high and low marsh plants. The lower reach has broader creeks with sediments formed from marsh deposits and sand transported in by coastal processes. The lower reach is transitional from the highly organic sediments of the upper marsh to the sandy near shore sediments of adjacent Cape Cod Bay. The tide range in adjacent Cape Cod Bay is large, ~10 ft (Chapter V), and the salt marsh areas are regularly flooded at high tide and the salt marsh creeks drain nearly completely with each ebb tide.

The large diurnal shifts in dissolved oxygen reflected within Namskaket Creek are consistent with the high productivity within the marsh, high levels of oxygen uptake by the organic matter rich marsh sediments and tidal changes in salinity and temperature which influence oxygen solubility (e.g. incoming tides transport oxygen rich waters). The relatively low chlorophyll a concentrations reflect the offshore waters, as the near complete exchange of tidal waters on each tide in the creeks does not allow for chlorophyll levels to build. The absence of a strong diurnal oxygen cycle, which is typically found in nitrogen enriched embayments (due to stimulation of phytoplankton), supports the concept that the marsh processes are the primary control on oxygen dynamics at this site. In fact, the daily average dissolved oxygen concentration varied inversely with the tidal amplitude suggesting that longer residence time and greater areal submergence of the marsh was responsible for the lowest oxygen observed oxygen levels. Further evidence for the dominance of marsh processes is the lack of linkage between the observed variations in chlorophyll and the extent of oxygen depletion. In embayments, oxygen minima are typically observed as a bloom declines (senesces), a pattern not seen at this site. Consistent with this latter observation is that the tidally averaged TN level at the mooring site is only 0.488 mg N L^{-1}. In embayment systems on Cape Cod, this TN level typically does not result in the level of oxygen depletion found in the salt marsh creeks of the Namskaket and adjacent Little Namskaket Estuaries. It is clear that the organic rich sediments of the salt marsh are a predominant control of oxygen levels. It should be noted that this level of TN is typical of salt marsh creeks, and does not indicate impairment in that type of environment.

Figure VII-2.   Aerial Photograph of the Namskaket Creek system in Orleans showing the location of the Dissolved Oxygen mooring deployment conducted in the Summer of 2003.
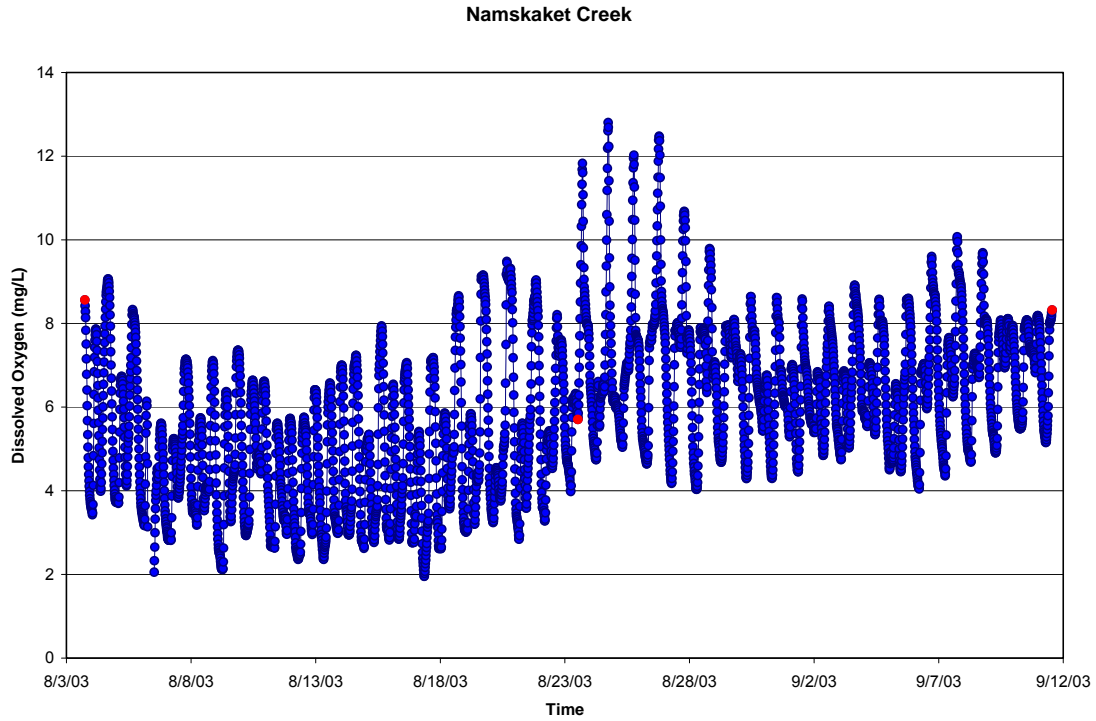
Figure VII-3.   Bottom water record of dissolved oxygen at the Namskaket Creek station, Summer 2003. Calibration samples represented as red dots.
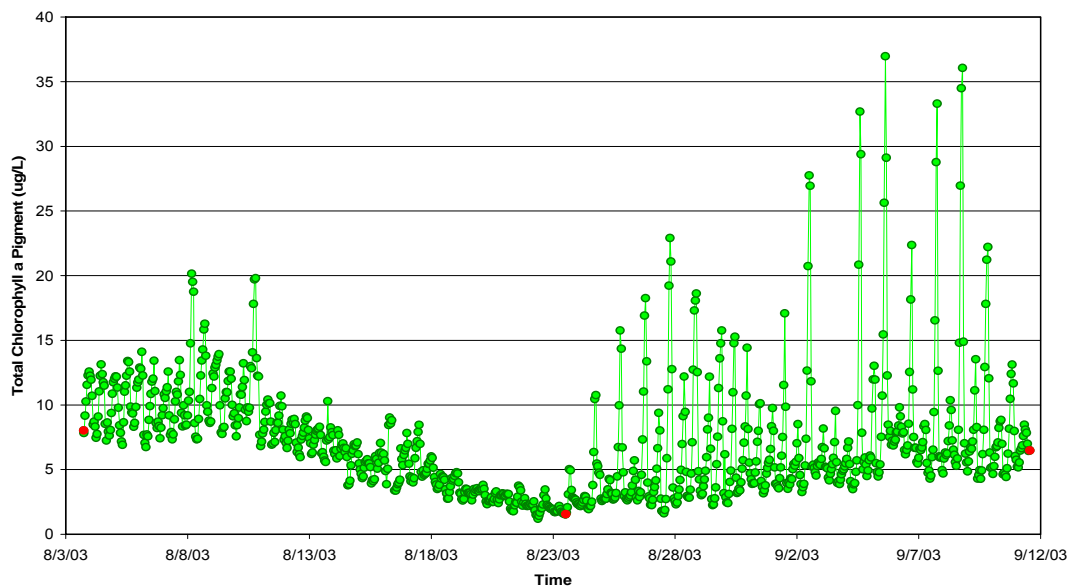
Figure VII-4.   Bottom water record of Chlorophyll-*a* in Namskaket Creek station, Summer 2003. Calibration samples represented as red dots.

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

Massachusetts Estuaries Project Town of Orleans: 2003	Dissolved Oxygen: Continuous Record, Summer 2003				
	Deployment Days	< 6 mg/L (% of days)	< 5 mg/L (% of days)	< 4 mg/L (% of days)	< 3 mg/L (% of days)
Rock Harbor	38.9	43%	25%	10%	2%
Namskaket	38.6	55%	34%	18%	16%
Little Namskaket	40.8	62%	43%	25%	9%

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

Embayment System	Start Date	End Date	Total Deployment (Days)	> 5 ug/L Duration (Days)	> 10 ug/L Duration (Days)	> 15 ug/L Duration (Days)	> 20 ug/L Duration (Days)	> 25 ug/L Duration (Days)
Rock Harbor								
Rock Harbor	8/3/2003	9/11/2003	37.6	18%	1%	0%	0%	0%
Mean				0.32	0.10	N/A	N/A	N/A
S.D.				0.76	0.03	N/A	N/A	N/A
Namskaket	8/3/2003	9/11/2003	38.8	63%	18%	4%	2%	1%
Mean				0.61	0.180	0.10	0.09	0.10
S.D.				1.68	0.09	0.04	0.03	0.02
Little Namskaket	8/1/2003	9/11/2003	40.7	2%	0%	0%	0%	0%
Mean				0.15	N/A	N/A	N/A	N/A
S.D.				0.04	N/A	N/A	N/A	N/A

Namskaket Creek and Little Namskaket Creek show similar patterns in oxygen and chlorophyll levels with some slight differences. Namskaket Creek drains a larger marsh area than Little Namskaket Creek, although the systems are similar in function and character of their central salt marsh creeks. It appears that with its larger surrounding salt marsh, the duration of low oxygen periods were greater for Namskaket Marsh, although the magnitude of depletion was the same for each system. Given that the basin being evaluated is the central tidal creek of an extensive salt marsh, the oxygen and chlorophyll records are consistent with a typical New England salt marsh system. The levels of oxygen depletion are similar to those recorded in other southeastern Massachusetts salt marsh dominated systems under low to background nitrogen loading.

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data is key part of the MEP Approach. Surveys were conducted in the vicinity of the Namskaket Creek System by the DEP Eelgrass Mapping Program as part of the MEP effort in 1995 and 2001. The primary use of the data is to indicate (a) estuarine regions that have historically or presently support eelgrass habitat, 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 1995 to 2001 (Figure VII-5); the period in which watershed nitrogen loading significantly increased to its present level. This temporal information can be used to determine the stability of the eelgrass community.

Eelgrass surveys were not undertaken for Namskaket Creek by the MassDEP Eelgrass Mapping Program (C.Costello), as this "basin" is the central tidal creek of a extensive salt marsh, similar to adjacent Little Namskaket Creek. Tidal creeks do not generally support eelgrass habitat, particularly when the creek nearly completely drains during each ebb tide, as is the case for Namskaket Creek. In addition, the 1951 analysis could not be performed due to the lack of adequate aerial photos. However, there is no evidence of eelgrass previously colonizing this system. The MEP Technical Team did confirm the lack of eelgrass in the tidal creeks to the Namskaket System while undertaking field surveys as part of the benthic regeneration and infauna studies and during the deployment and recovery of the instrument moorings.

In contrast, eelgrass is present offshore of the inlet to Namskaket Creek as well as Little Namskaket Creek and Rock Harbor. Based on the 2001 eelgrass survey conducted by the DEP Eelgrass Mapping Program offshore, there was evidence of a potential decline in the coverage of the offshore beds between 1995 and 2001 (Table VII-3). However, it is not possible at this time to determine if this represents an anthropogenically driven decline or natural variation at this site. Additional temporal sampling is planned to address this issue.
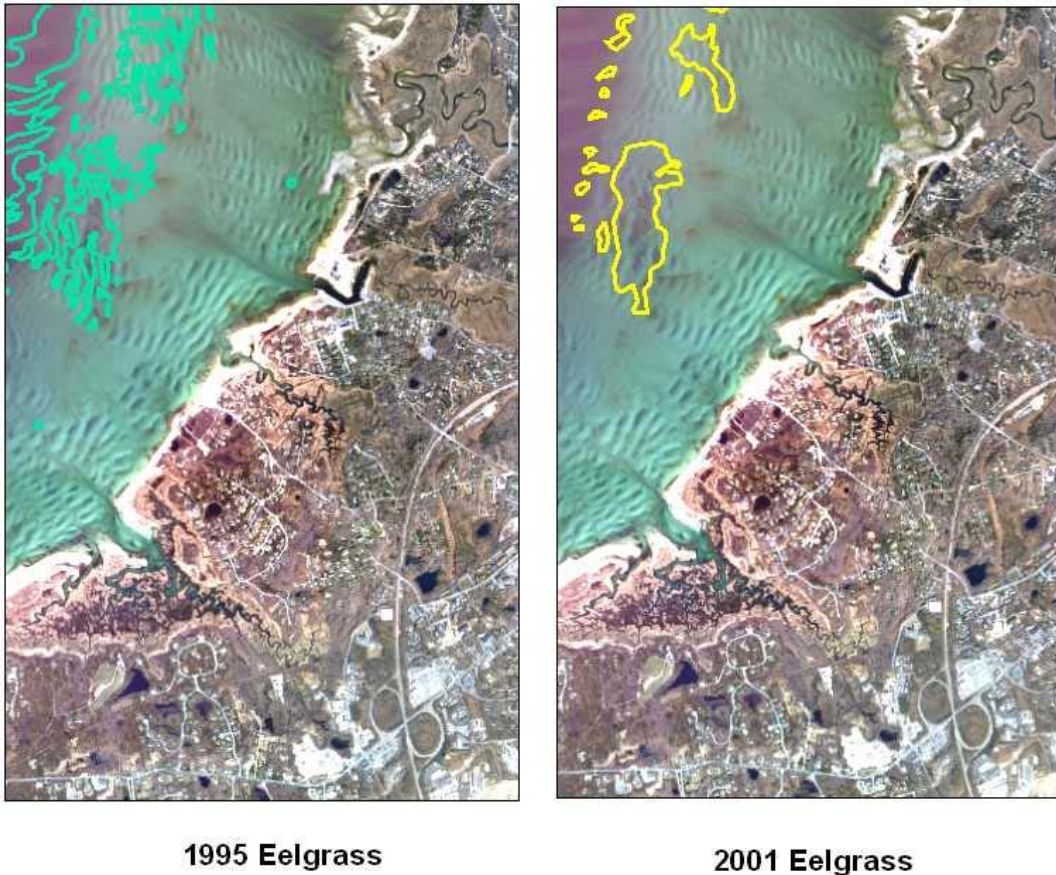
Figure VII-5.   Eelgrass bed distribution immediately offshore the Namskaket Creek, Rock Harbor and Little Namskaket Creek systems. The 1995 coverage is depicted by the green outline and the 2001 coverage the yellow outline, which circumscribes the eelgrass beds as mapped by DEP Eelgrass Program. There is no evidence that these three systems have ever supported eelgrass habitat, as they are primarily tidal salt marshes.

Based upon all available information, it appears that the Namskaket Estuary is not structured to support eelgrass habitat, as is also the case for nearby, Little Namskaket Creek. Therefore, threshold development for protection/restoration of this system will focus on infaunal habitat quality. This is typical for New England salt marshes, which are naturally organic and nutrient rich and generally contain little water in the creeks at low tide. This conclusion has been confirmed in a wide range of salt marsh dominated basins throughout southeastern Massachusetts by the MEP Technical Team. The eelgrass data for the Namskaket Estuary are consistent with the results of the benthic infauna analysis and the water quality data for this system (see below).

Table VII-3.   Changes in eelgrass coverage offshore from the Namskaket Creek, Rock Harbor and Little Namskaket Creek systems within the Town of Orleans over the past half century (C. Costello). The absence of eelgrass within these salt marsh systems is typical of tidal marshes throughout New England.

Temporal Change in Eelgrass Coverage				
Embayment	1951 Acreage	1995 Acreage	2001 Acreage	% Loss 1995 - 2001
Rock Harbor	NA[1]	0	0	NA[1]
Namskaket Creek	NA[1]	0	0	NA[1]
Little Namskaket Creek	NA[1]	0	0	NA[1]
Nearshore Cape Cod Bay	unavailable	**294.51**	**229.47**	**22%**
1 -- no historical evidence of eelgrass in this basin				

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 7 locations along the central tidal creek of the Namskaket Estuarine System (Figure VII-6). In some cases multiple assays were conducted. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, although there are no eelgrass beds in the Namskaket Marsh system, this is likely to have more to do with the structure of the system. As such, to the extent that Namskaket Marsh can support healthy infaunal communities given specific nutrient conditions in the water column, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

Analysis of the evenness and diversity of the benthic animal communities was also used to support the density data and the natural history information (Table VII-4). The evenness statistic can range from 0-1 (one being most even), while the diversity index does not have a theoretical upper limit. The highest quality habitat areas, as shown by the oxygen and chlorophyll records and eelgrass coverage, have the highest diversity (generally >3) and

evenness (~0.7). The converse is also true, with poorest habitat quality found where diversity is <1 and evenness is <0.5.

The Infauna Study indicated that the tidal creeks of the Namskaket Estuary are presently supporting a typical salt marsh infaunal habitat. Infauna communities within the tidal creek were indicative of the organic rich environment typical of salt marshes and consistent with the observed levels of oxygen depletion and watercolumn TN. The communities within the upper reach had moderate to high numbers of individuals with lower numbers of species and diversity within the transitional environment of the lower reach. The observed communities were typical of New England salt marsh creek bottom environments in summer. The communities generally contained some organic enrichment tolerant species. However, species like *Capitella* and *Streblospio,* typically observed in impaired embayment habitats, like nearby Rock Harbor lower basin, generally did not dominate and there were significant numbers of crustaceans and polychaetes.

Overall, the Infauna Survey indicated that most areas within Namskaket Marsh are supporting infauna habitat typical of organic rich New England salt marshes, hence high quality relative to this estuarine ecosystem type. This is supported by the absence of macroalgal accumulations and algal mats within the creek bottoms, which can result if there is "excessive" external nitrogen loading. The absence of macroalgal accumulations is consistent with the relatively low total nitrogen levels within this system, 0.42-0.66 mg N L^{-1} (tidally averaged), compared to a similar marsh, Cockle Cove Creek (Chatham), which supports high quality habitats, both emergent marsh and creek bottom, at levels of 2 mg TN L^{-1}. Based upon all lines of evidence it appears that the Namskaket Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment.

Figure VII-6.   Aerial photograph of the Namskaket Marsh system showing location of benthic infaunal sampling stations (blue symbol).

Table VII-4.   Benthic infaunal community data for the Namskaket Creek 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 0.018 m2). Stations refer to map in figure VII-6, (N) is the number of samples per site.

Location	Sta ID (N)	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Namskaket Creek						
Upper Reach	Sta. 1 (2)	4	103	4	0.31	0.18
	Sta. 3 (2)	4	224	4	1.12	0.75
	Sta. 4 (2)	11	568	9	2.41	0.71
	Sta. 5 (2)	7	75	6	2.47	0.88
Lower Reach	Sta. 6 (2)	4	45	5	1.35	0.79
	Sta. 7 (2)	4	60	NA	1.06	0.76
	Sta. 8 (1)	8	48	NA	2.31	0.77

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll a). Additional information on temporal changes within each sub-embayment and its watershed further strengthen the analysis. These data were collected by the MEP to support threshold development for the Namskaket Creek estuarine system and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the water quality monitoring baseline collected by the Town of Orleans' Water Quality Monitoring Program.

At present, the Namskaket Estuary is showing high habitat quality throughout its salt marsh reach. The upper reach appears to be a fully functional tidal salt marsh with deeply incised narrow creeks surrounded by extensive emergent marsh. This reach is typical of New England "pocket" marshes, with smaller tidal creeks and a marsh plain dominated by low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) plant communities with patches of fringing brackish marsh vegetation (*Juncus, Phragmites*). The lower reach of the marsh supports a large wetland area to the west along with larger tidal creeks. The lower portion of the system is also heavily influenced by sand transport via nearshore coastal processes associated with adjacent Cape Cod Bay. Plant communities in the lower reach are similar to the upper reach except that there is less fringing brackish water species and the marsh grades to barrier beach/dune vegetation near the tidal inlet. The tide range in adjacent Cape Cod Bay is large, ~10 ft (Chapter V), and the salt marsh areas are regularly flooded at high tide and the salt marsh creeks nearly drain completely with each ebb tide.

All of the key habitat indicators are consistent within Namskaket Marsh, and particularly its tidal creeks, supporting high quality habitat in line with the system's salt marsh structure and function (Chapter VII). Assessment of habitat quality must necessarily consider the natural function and tolerances of the specific estuarine ecosystem being evaluated, specifically:

Eelgrass: Eelgrass is not present within the estuarine reach of this system (or in the adjacent salt marsh, Little Namskaket Creek). Based upon all available information, it appears that the Namskaket Estuary is not structured to support eelgrass habitat, as is also the case in Little Namskaket Creek. This is typical for New England salt marshes, which are naturally organic and nutrient rich and generally contain little water in the creeks at low tide. This conclusion has been confirmed by the MEP Technical Team in a wide range of salt marsh dominated basins throughout southeastern Massachusetts. Therefore, threshold development for protection/restoration of this system will focus on infaunal habitat quality. The eelgrass data for the Namskaket Estuary are consistent with the results of the benthic infauna analysis and the water quality data for this system (see below).

Water Quality: The dissolved oxygen records indicate that the central tidal salt marsh creek of the extensive Namskaket salt marsh system has periodic oxygen depletion to 2 mg L^{-1} (Table VII-1). Such oxygen depletion is typical of organic and nutrient rich estuarine systems and in embayments indicates impaired habitat quality. However, salt marshes are nutrient and organic matter enriched as part of their ecological design, with a natural consequence being that they experience periodic oxygen depletion during warmer summer months. The observed level of

oxygen depletion in Namskaket Creek is expected, and was nearly identical to that of adjacent Little Namskaket Creek and other salt marsh dominated systems in the MEP study region.

The large diurnal shifts in dissolved oxygen reflected within Namskaket Creek are consistent with the high productivity within the marsh, high levels of oxygen uptake by the organic matter rich marsh sediments and tidal changes in salinity and temperature which influence oxygen solubility (e.g. incoming tides transport oxygen rich waters). The relatively low chlorophyll a concentrations reflect the offshore waters, as the near complete exchange of tidal waters on each tide in the creeks does not allow for chlorophyll levels to build up. A number of observations support the concept that the marsh processes are the primary control on oxygen dynamics in this system (Section VII.2). These include the importance of tidal over diurnal cycles; the lack of linkage between oxygen depletion, chlorophyll levels, TN concentrations (0.488 mg N L^{-1}) and the apparent association of longer duration low oxygen periods and the area of salt marsh up gradient of the measurement site.

Since the oxygen record is primarily from the boundary of the upper and lower central tidal creek, this site should experience the lowest oxygen levels within the main creek of this system on the ebbing tide. As the oxygen dynamics are associated with the natural structure and function of this estuarine system, Namskaket Creek is considered to be supporting high quality habitat throughout its tidal reach.

Infaunal Animal Communities: Infauna communities within the central tidal creek of the Namskaket Estuary are presently supporting infaunal habitat typical of the organic rich environment of New England salt marshes in summer. The communities are consistent with the observed levels of oxygen depletion and watercolumn TN. The communities within the upper reach had moderate to high numbers of individuals, and low species numbers, with lower numbers of individuals and species within the transitional environment of the lower reach. The communities generally contained some organic enrichment tolerant species. However, species like *Capitella* and *Streblospio,* typically observed in impaired embayment habitats, like nearby Rock Harbor lower basin, did not dominate while there were also significant numbers of crustaceans and polychaetes.

Overall, the Infauna Survey indicated that most areas within Namskaket Marsh are supporting infauna habitat typical of organic rich New England salt marshes, hence high quality relative to this estuarine ecosystem type. This is supported by the absence of macroalgal accumulations and algal mats within the creek bottoms which can result if there is "excessive" external nitrogen loading. The absence of macroalgal accumulations is consistent with the relatively low total nitrogen levels within this system, 0.42-0.66 mg N L^{-1} (tidally averaged). This is in comparison to a similar marsh, Cockle Cove Creek (Chatham), which supports high quality habitats, both emergent marsh and creek bottom, at levels of 2 mg TN L^{-1}. Based upon all lines of evidence it appears that the Namskaket Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment.

Table VIII-1.	Summary of Nutrient Related Habitat Health within the Namskaket Marsh Estuary on the Cape Cod Bay shore of the Towns of Orleans and Brewster, MA, based upon assessment data presented in Chapter VII. The tidal reach of this estuary is a typical New England salt marsh with a large central tidal creek and as such it is nutrient and organic matter enriched.

Health Indicator	Namskaket Marsh Estuary	
	Upper Salt Marsh	Lower Salt Marsh
Dissolved Oxygen	--[1]	H[1]
Chlorophyll	--[2]	H[2,3]
Macroalgae	H[4]	H[4]
Eelgrass	--[5]	--[5]
Infaunal Animals	H[6]	H[7]
Overall:	**H**	**H**

1-- oxygen mooring placed at upper margin of the lower reach, within the central tidal creek, oxygen dynamics were consistent with a naturally organic matter and nutrient rich New England salt marsh, oxygen depletions are typical of pristine salt marsh creeks. Periodic oxygen depletions to 2 mg/L and frequently <4 mg/L.

2 -- tidal waters ebb nearly completely at low tide, chlorophyll levels reflect floodwaters.

3 – moderate chlorophyll a levels generally 2-8 ug/L, but periodically >10 ug/L, oxygen dynamics do not appear linked to chlorophyll levels.

4 – *Ulva* and drift algae and surface algal mats very sparse to absence

5 – no evidence that this estuarine reach is supportive of eelgrass, as it is a salt marsh tidal creek, which drains at low tide.

6 -- moderate to high numbers of individuals and low species numbers, species typical of organic rich New England salt marshes in summer (polychaetes and crustaceans).

7 -- low numbers of individuals and species, species typical of organic rich New England salt marshes in summer, physical processes associated with inlet also have influence in this estuarine reach (unstable substrate).

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

VIII.2. THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout and embayment system, is to first identify a sentinel location within the embayment and second to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality. The sentinel location is selected such that the restoration (or protection) of that one site will necessarily bring the other regions of

the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined, the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved.

As a salt marsh dominated estuary, Namskaket Marsh does not support eelgrass habitat. As a result, threshold development for protection/restoration of this system focuses on infaunal habitat quality. The primary mechanism for infaunal habitat quality decline in salt marsh creeks of this type is through stimulation of macroalgal production and accumulation.

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Namskaket 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).

Since Namskaket Marsh is presently below the level of nitrogen loading that would cause impairment to its infaunal habitats (i.e. below its nitrogen threshold level), a conservative estimate of the threshold was established. The threshold was based upon the site-specific data mentioned above and comparison to other similar systems on Cape Cod where detailed nitrogen threshold studies have been completed. This inter-estuarine comparison focused upon similar salt marshes which are presently experiencing higher nitrogen levels, with and without impairment.

A detailed nitrogen threshold analysis of Cockle Cove Creek (Chatham), a similarly configured salt marsh to Namskaket Creek, has recently been completed (SMAST 2006). In addition to having similar structures, Cockle Cove Creek and Namskaket Creek both support similar benthic communities, macroalgal accumulations are sparse to absent in both systems and tidal velocities within the central creek are similar. In addition, the infaunal habitats within Namskaket and Cockle Cove Marsh are similar in composition and diversity (dominated by polychaetes and crustaceans, with some mollusks). The dominant species (*Leptocheirus, Paranais*) was also observed in a study of a healthy salt marsh, Great Sippewissett Marsh on Cape Cod (Wiltse 1984).

Based on MEP analysis, it was ascertained that the major infaunal habitat issue related to nitrogen levels in salt marshes (e.g. Namskaket Marsh and Cockle Cove) was associated with the potential accumulation of macroalgae within the tidal creek bottom. Accumulations of macroalgae have been observed in a variety of nitrogen enriched salt marsh systems, For example Mashapaquit Marsh, West Falmouth Harbor and Aucoot Cove salt marsh (Town Marion). These marshes differ from Namskaket and Cockle Cove Creek, in that they do not empty at low tide and they support broad creeks with low tidal velocities. These geomorphic differences allow these systems to grow and accumulate algae (Ulva), which can then "smother" benthic communities. The MEP Technical Team assessed tidal velocities of these systems using a numerical hydrodynamic model. Cockle Cove Creek, Namskaket Creek and Little Namskaket Creek were found to have similar tidal velocities (1.1 ft sec^{-1}, 1.24 sec^{-1}, 1.13 ft sec^{-1}, respectively). None of these systems have macroalgal accumulations. In contrast,

Mashapaquit and Aucoot Marshes had much lower tidal velocities (<0.5 ft sec^{-1}) and macroalgal accumulations. Algal accumulation did not appear to be controlled by nitrogen level alone, as Cockle Cove Creek had nitrogen levels 3-5 fold higher than the other systems, predominantly in plant available forms (nitrate, ammonium). The velocity data relates to the inability of drift algae to accumulate if there is no basin or low velocity areas to allow for settling. This is the case in Namskaket Creek.

A principal component of the high tolerance of salt marsh systems to nitrogen inputs from groundwater and surface water inflows is that unlike embayments, creek waters cannot accumulate nutrients over multiple tidal cycles as embayments do. In addition, increasing the nitrogen concentration in the tidal waters that flood the marsh plain will have a negligible or possibly a stimulatory effect on marsh primary and likely secondary production (i.e. an enhancement of habitat). In addition, since the inflowing fresh waters flow down gradient through the marsh creek and out to the Sound, the nitrogen level will never exceed the inflowing freshwater nitrogen level.

For the Cockle Cove Creek system, it was determined that a highly conservative nitrogen threshold would yield a total nitrogen level of $\leq$2 mg N L-1 throughout the salt marsh, e.g. from headwaters to tidal inlet. As this system closely resembles the structure and hydrodynamics of Namskaket Creek, this threshold level appears to be appropriate for Namskaket Marsh as well. It should be noted that the upper most marsh reach of Cockle Cove is currently exposed to 2-3 mg N L^{-1}, without discernable habitat impairment. Also, it is important to note that since the creek bottom sediments remove nitrate during transport, the TN concentration declines along the tidal reach. As such, the lower tidal reach has a significantly lower tidally averaged concentration compared to the headwaters. This can be seen in the existing TN gradient, where tidally averaged TN in Namskaket Marsh headwaters are 0.662 mg N L^{-1} and 0.421 mg N L^{-1} at the inlet, similarly in Little Namskaket Marsh the range is 1.044 - 0.604 mg N L^{-1}.

Putting all the assessment elements together, it appears that for Namskaket Creek, the critical values are a total nitrogen level of 2 mg N L^{-1} in the headwaters and a level of 1 mg N L^{-1} at the border of the upper and lower reach (Station WMO-23). As this upper/lower boundary station is the uppermost long-term marine water quality sampling site and integrates all of the watershed and upper marsh nitrogen inputs and removals, it was selected as the sentinel station for this system (WMO-23). The threshold (tidally averaged) total nitrogen level of 1 mg N L^{-1}.was determined to be appropriate for the sentinel station (WMO-23). It should be noted that the tidally averaged total nitrogen level at the middle marsh station in Cockle Cove Creek is currently 1.378 mg N L^{-1} and the tidal inlet station shows concentrations of 0.472 mg N L^{-1}, consistent with the 1 mg N L^{-1} at the sentinel station in Namskaket Marsh.   This threshold applies as long as the tidal creek maintains its present hydrodynamic characteristics (flushing and velocity). The nitrogen threshold for Namskaket Marsh is intentionally conservative based upon all available data from comparable systems. However, it indicates that additional nitrogen may enter this system without impairment of its habitat quality throughout the estuary. The nitrogen loads associated with the threshold concentration at the sentinel location are discussed in Section VIII.3, below.

VIII.3 DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Namskaket Creek system. Total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI.

Contrary to most other estuarine systems evaluated as part MEP, the threshold concentration was set higher than present conditions, meaning that the system would be allowed to have a higher load than present and still be able to meet the threshold. Therefore, watershed nitrogen loads were sequentially raised in the model until the nitrogen levels reached the threshold level at the sentinel station (WMO-23) chosen for Namskaket Creek. It is important to note that load increases could be produced by increasing of any or all sources of nitrogen to the system. The load increases presented below represent only one of a suite of potential approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of loading that will be allowable for this system. A comparison between present watershed loading and the loadings for the modeled threshold scenario is provided in Tables VIII-1.

As shown in Table VIII-2, the threshold set for this system would allow up to 3.6 times (261% increase) the present watershed loading. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1. It should be noted that should the groundwater N plume resulting from discharge from the Tri Town Septage Treatment Facility begin to discharge to Namskaket Marsh, that its load would not in and of itself, exceed the threshold loading for this estuarine system. In fact, at present levels the Facility discharges 1196 kg/yr or an average of 3.28 kg/d is only ~15% of the additional N loading increase at the N threshold of 22.22 kg/d (total 31.51 kg/d versus present 9.29 kg/d) in the Namskaket Marsh subwatershed or ~10% of the total watershed increase at the N threshold of 33.21 kg/d (45.89 kg/d at threshold versus present 12.685 kg/d). Given the loads, it appears that accommodating entry of the Tri Town plume into Namskaket Marsh should be relatively straight forward.

Table VIII-3 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-3, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent 'worst-case' summertime conditions. The benthic flux for this modeling effort is modified from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Cape Cod Bay, as discussed in Section VI.2.6.1.

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-4. To achieve the threshold nitrogen concentrations at the sentinel station, increases in average TN concentrations of typically greater than 50% occur in the system, between the main harbor basin and the marsh.

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 embayment.

Table VIII-2.	Comparison of sub-embayment *total watershed loads* (including septic, runoff, and fertilizer, and the WWTF) used for modeling of present and threshold loading scenarios of the Namskaket Creek system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.		
sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Namskaket marsh	9.290	31.510	+239.2%
Namskaket Creek (freshwater)	3.395	14.381	+323.6%
System Total	12.685	45.890	+261.8%

Table VIII-3.	Threshold sub-embayment loads used for total nitrogen modeling of the Namskaket Creek 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)
Namskaket marsh	31.510	0.118	-0.317
Namskaket Creek (freshwater)	14.381	-	-
System Total	45.890	0.118	-0.317

| Table VIII-4.	Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the Namskaket Creek system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The threshold station is shown in bold print.			
Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Namskaket – mouth	WMO-22	0.421	0.637	+51.4%
Namskaket – lower	**WMO-23**	0.488	0.937	+92.2%
Namskaket – upper	WMO-24	0.662	2.054	+210.1%
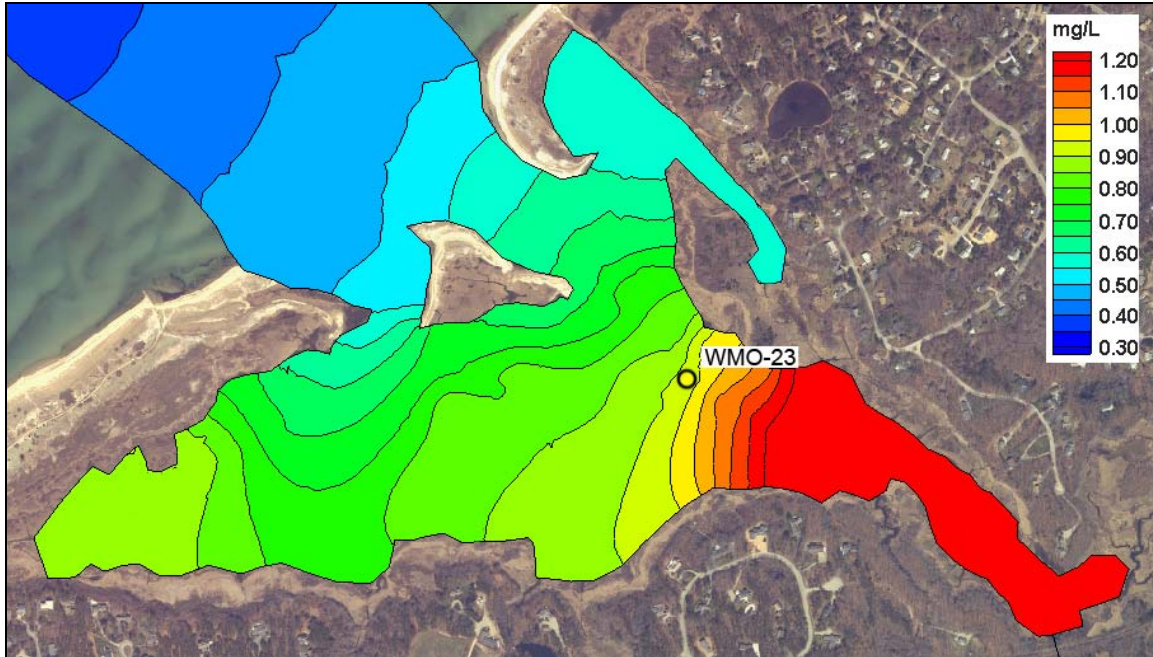
Figure VIII-1.   Contour plot of tidally averaged modeled total nitrogen concentrations (mg/L) in the Namskaket Creek system for threshold conditions at WMO-23, the sentinel station (1.0 mg/L) and a maximum concentration of 2.0 mg/L in the upper portion of the marsh. The plot shows the entire area of Namskaket Marsh that is flooded at high tide.

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.

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.

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

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

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

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

Cape Cod Commission. 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"

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.

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

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. 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.

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

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

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

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

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. 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.

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.

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.

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

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

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

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.

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, (1994a). Freshwater flow into a coastal embayment: groundwater and surface water inputs. Limnology and Oceanography 39: 1928-1944.

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

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

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.

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

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

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

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]

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

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

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

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.

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".

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

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

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

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

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

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