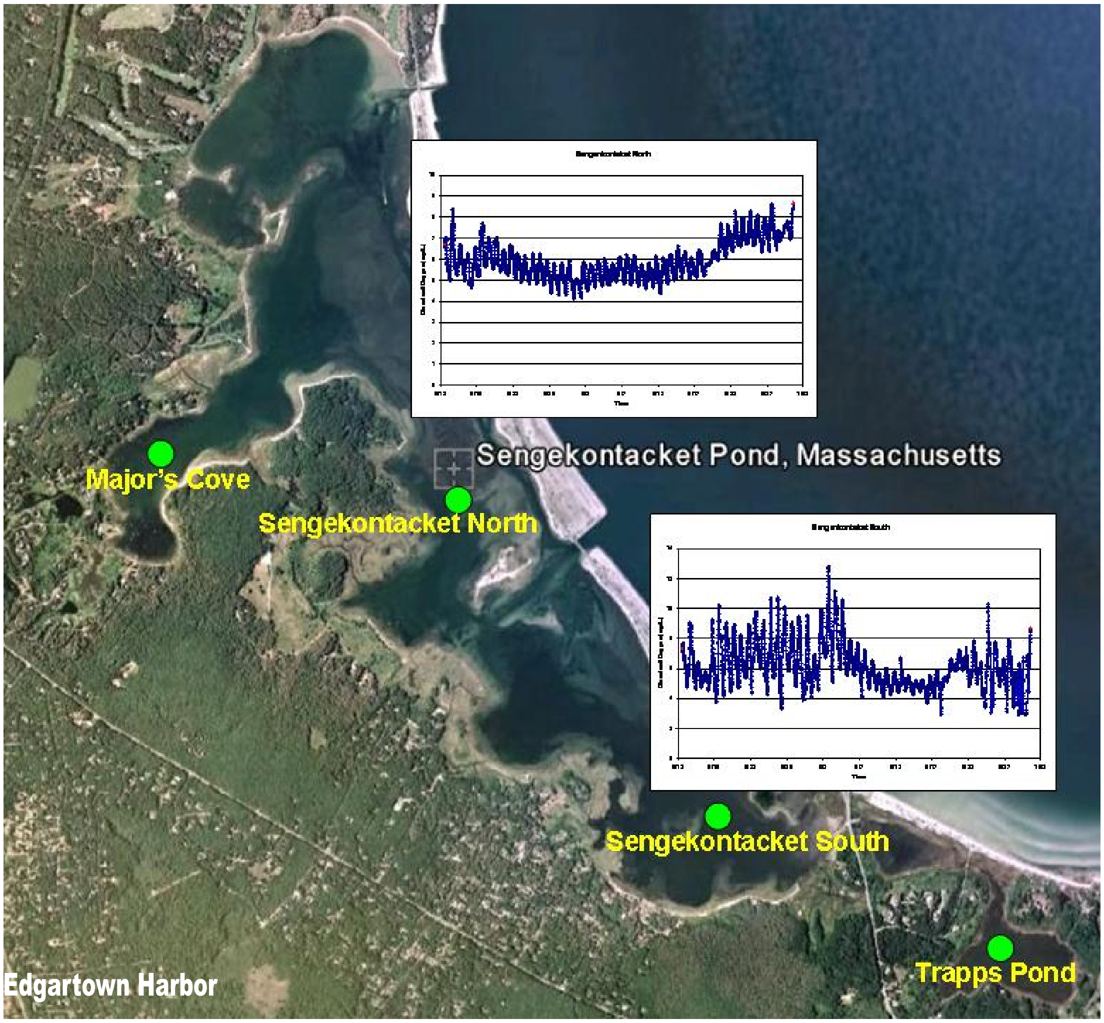
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Sengekontacket Pond System, Towns of Oak Bluffs and Edgartown, MA



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

FINAL REPORT – January 2011

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Brian Howes
Roland Samimy
David Schlezinger
Ed Eichner

Trey Ruthven
John Ramsey

William Wilcox

Contributors:

US Geological Survey
Don Walters and John Masterson

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

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

SMAST Coastal Systems Program
Jennifer Benson, Michael Bartlett, Sara Sampieri and Elizabeth White

Martha's Vineyard Commission
Chris Seidel

ACKNOWLEDGMENTS

The Massachusetts Estuaries Project Technical Team would like to acknowledge the contributions of the many individuals who have worked tirelessly for the restoration and protection of the critical coastal resources of the Sengekontacket Pond Embayment and supported the application of the Linked Watershed-Embayment Model to Determine the Critical Nitrogen Loading Threshold for this estuarine system. Without these stewards and their efforts, this project would not have been possible.

First and foremost we would like to recognize and applaud the significant time and effort in data collection and discussion spent by members of the Martha's Vineyard Commission / Oak Bluffs / Edgartown Shellfish Department's Water Quality Monitoring Program. These individuals gave of their time to develop a consistent and sound nutrient related water quality from this system for over a decade, without which the present analysis would not have been possible.

Staff from the Martha's Vineyard Commission and the Towns of Oak Bluffs and Edgartown have provided essential insights toward this effort. Of particular note have been the efforts of Dave Grunden (Oak Bluffs Shellfish Constable) and Paul Bagnall (Edgartown Shellfish Constable/Marine Biologist) and Bill Wilcox (MVC Water Resources Planner), who have spent countless hours reviewing data and information with MEP Technical Team members in support of the MEP analysis of Sengekontacket Pond. In addition, the MVC contributed historical information and Chris Seidel, MVC GIS Specialist provided significant support for the MEP land-use analysis, particularly analysis of parcel information and site-specific loading information, as well as GIS support.

In addition to local contributions, technical, policy and regulatory support has been freely and graciously provided by MaryJo Feurbach and Art Clark of the USEPA; and our MassDEP colleagues: Rick Dunn and Dave DeLorenzo. We are also thankful for the long hours in the field and laboratory spent by the technical staff, interns and students within the Coastal Systems Program at SMAST-UMD in the analysis of water quality samples and the conduct of surveys of estuarine resources.

Support for this project was provided by the Town of Edgartown through the efforts of the Joint Sengekontaket Pond Committee, the MassDEP, and the USEPA.

PROPER CITATION

Howes B.L., E.M. Eichner , T. Ruthven, R.I. Samimy, J. S. Ramsey, D.R. Schlezinger, (2010). Linked Watershed-Embayment Model to Determine the Critical Nitrogen Loading Threshold for the Sengekontacket Pond System, Oak Bluffs and Edgartown, Massachusetts. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

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I. INTRODUCTION

The Sengekontacket Pond Embayment System is a complex estuary located within the Towns of Oak Bluffs and Edgartown on the island of Martha's Vineyard, Massachusetts with an eastern shore bounded by water from Vineyard / Nantucket Sound (Figure I -1). The Sengekontacket Pond watershed is distributed primarily amongst the Towns of Oak Bluffs and Edgartown, with a small portion of the upper watershed extending into the Town of West Tisbury. A large region of the upper watershed is comprised primarily of "protected" forest land (Manuel F. Correllus State Forest). Though it is true that land-uses closest to an embayment generally have greater impact than those in the upper portions of the watershed, which are subject to nitrogen attenuation during transport through natural aquatic systems (e.g. ponds, rivers, wetlands etc.) prior to discharge to the embayment, effective restoration of the Sengekontacket Pond System will require consideration of all sources of nitrogen load. That nearly (a small portion of the upper watershed extends into West Tisbury) the entire watershed to the Sengekontacket Pond system is contained within two Towns, Oak Bluffs and Edgartown, makes development and implementation of a comprehensive nutrient management and restoration plan for this system more challenging as watershed-wide planning can sometimes be complicated by the need for consensus among multiple municipal jurisdictions.

Figure I-1. Location of the Sengekontacket Pond Estuarine system, Island of Martha's Vineyard, Towns of Oak Bluffs and Edgartown, MA. Sengekontacket Pond is a great salt pond, supporting two tidal inlets through the barrier beach which allows exchange of water with Vineyard / Nantucket Sound.

The Sengekontacket Pond Embayment System is a moderately complex coastal lagoonal type estuary with a smaller tributary salt pond, Trapps Pond. The overall system supports two armored inlets, through which tidal exchange with adjacent Vineyard Sound occurs, and multiple small un-named tributary coves as well as two major sub-embayment features: (1) Majors Cove in the northern portion of the system and (2) Trapps Pond in the southern portion of the system. While tidal flows within Sengekontacket Pond are unrestricted due to the width and depth of the channels, exchange with Trapps Pond is significantly restricted. This tidal restriction reduces the flushing of Trapps Pond waters and increases the sensitivity of the Pond to nitrogen loading.

Tidal exchange between the main basin of Sengekontacket Pond and the Sound is through separate northern and southern inlets. The northern inlet supplying Vineyard / Nantucket Sound water into the northern portion of the main basin of Sengekontacket Pond is significantly smaller than the second more southern inlet that is centrally located along the barrier beach separating Sengekontacket Pond from the adjacent sound. The second more southern inlet is the main inlet to Sengekontacket Pond and is less prone to shoaling on the Sengekontacket Pond side of the inlet, unlike the smaller inlet located to the north. Floodwater from Vineyard / Nantucket Sound enters the large main basin of Sengekontacket Pond from both the northern and more southern primary inlet and circulates through channels and across flats making its way up the pond into Majors Cove as well as past the sand spits known as Haystack Point and Brant Point to enter Trapps Pond (Figure I-2).

The Sengekontacket Pond Embayment System and most of its watershed is sited within the Nantucket Moraine sediments consisting mainly of folded pre-Wisconsin clay, sand, gravel and glacial till overlain by Wisconsin drift (Woodworth and Wigglesworth 1934). Only a portion of the upper watershed is sited in the sandy outwash plain to the south. These sediments were deposited as the ice sheets retreated at the end of the last glacial period.

The late Wisconsinan Laurentide ice sheet reached its maximum extent and southernmost position about 20,000 years before present (BP), as indicated by the presence of terminal moraines on Martha's Vineyard and Nantucket and the southern limit of abundant gravel on the sea floor of Nantucket Sound and Vineyard Sound (Schlee and Pratt, 1970; Oldale, 1992; Uchupi et al., 1996). The lobate ice front was comprised of the Buzzards Bay lobe that deposited the moraine along the western part of Martha's Vineyard, the Cape Cod Bay lobe that deposited the moraines across eastern Martha's Vineyard and Nantucket, and the South Channel lobe that extended east toward Georges Bank (Oldale and Barlow, 1986; Oldale, 1992). During the retreat of the ice sheet, approximately 18,000 years BP, the Nantucket Moraine was deposited and the outwash plain that forms the central and southern portion of Martha's Vineyard. While the watershed was formed on the order of 18,000 years ago, the estuary of Sengekontacket is a much more recent formation, likely 2,000 - 4,000 years ago as sea level flooded the present basin.

The enclosed Sengekontacket Pond estuary appears to have been formed as a composite estuary, where it appears that a valley (Majors Cove) possibly partially formed from kettles and stream channels was drowned by rising sea level, with subsequent formation of a lagoonal estuary to seaward, created by the formation of a barrier beach via spit growth primarily from the northern shore. While formation of the upper tidal reach of Majors Cove is less certain, the lagoon portion of Sengekontacket Pond is not. Lagoonal estuaries form parallel to coasts and are a major type of estuary along the east coast of the United States. The finding that beach deposits constitute the Vineyard / Nantucket Sound shoreline of Sengekontacket Pond favors its formation as a "lagoon". What is clear is that it is presently functioning as an estuarine system and is showing clear signs of nitrogen enrichment. For the MEP analysis, the

Sengekontacket Pond estuarine system was considered as 2 main basins, a northern basin and a southern basin, with 2 tributary sub-embayments, Majors Cove and Trapps Pond.

Figure I-2. Study region for the Massachusetts Estuaries Project analysis of the Sengekontacket Pond Embayment System. Tidal waters enter the Pond through two inlets passing through the barrier beach and allowing tidal exchange with waters from Vineyard / Nantucket Sound. Freshwaters enter from the watershed primarily through direct groundwater discharge as there are no significant surface water inflows to this system.

The formation of the Sengekontacket Pond System has and continues to be greatly affected by coastal processes, specifically the role that the barrier beach plays in separating the pond from Vineyard / Nantucket Sound source waters. The ecological and biogeochemical structure of the pond is likely to have changed over time as the barrier beach naturally breached in different locations along the barrier beach and intermittently closed in as a function of storm frequency and intensity. It is almost certain that the "open" nature of the existing main basin is geologically an artificial phenomenon, and that the pond would naturally exist as a generally closed system with occasional inlets opening up from storm activity.

The primary ecological threat to the Sengekontacket Pond embayment system as a coastal resource is degradation resulting from nutrient enrichment. Although the watershed and the Pond have some issues relative to bacterial contamination, this does not appear to be having large ecosystem-wide impacts. Bacterial contamination causes closures of shellfish harvest areas, however and in contrast, loading of the critical eutrophying nutrient (nitrogen) to the Sengekontacket Pond System has greatly increased over 1950 levels. The nitrogen loading to this system, like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater and WWTF discharges to the extent any facilities exist in the watershed to Sengekontacket Pond. This is discussed in detail in Chapter IV.

The towns of Martha's Vineyard have been among the fastest growing towns in the Commonwealth over the past two decades and the Town of Edgartown does have a centralized wastewater treatment system, however, the site of discharge of its tertiary treated effluent is located in the Edgartown Great Pond watershed. Nevertheless, large portions of the Sengekontacket Pond watershed are not connected to any municipal sewerage system. Rather, these unsewered areas rely on privately maintained septic systems for on-site treatment and disposal of wastewater. As existing and probable increasing levels of nutrients impact the coastal embayments of the Towns of Oak Bluffs and Edgartown, water quality degradation will accelerate, with further harm to invaluable environmental resources of the towns and the Island on the whole.

As the primary stakeholders to the Sengekontacket Pond system, the Towns of Oak Bluffs and Edgartown, in collaboration with the Martha's Vineyard Commission (MVC), have been among the first communities to become concerned over perceived degradation of their coastal embayments. Over the years, this local concern has led to the conduct of numerous studies (see Chapter II) of both barrier beach stability and nitrogen loading to the system such as: 1) Wave and Sediment Transport Modeling of Existing Conditions, Beach Road Protection Study, Oak Bluffs/Edgartown, Martha's Vineyard, Draft of October 2, 1996, Fugro East Inc., a report prepared for the Massachusetts Highway Department, 2) Impact Analysis (of Nitrogen Loading) on Sengekontacket Pond, 1994, Draft Report, Whitman & Howard and 3) the Nutrient Loading and Management Strategies at Sengekontacket Pond, August 5, 1999, Arthur Gaines, the Marine Policy Center of the Woods Hole Oceanographic Institution, a report prepared for the Friends of Sengekontacket. While critical historical studies have been considered in the MEP analysis of Sengekontacket Pond, key in the MEP effort has been the Sengekontacket Pond Water Quality Monitoring Program, spearheaded by the MVC and supported by private, municipal, county and state funds (most recently Massachusetts 604(b) grant program) with technical assistance by the Coastal Systems Program at SMAST-UMD. This effort provides the quantitative water column nitrogen data (1995,1996 and 2003-2009) required for the implementation of the MEP's Linked Watershed-Embayment Approach used in the present study.

Since the initial results of the Water Quality Monitoring Program and the land-use studies indicated that parts of the Sengekontacket Pond system are presently impaired by land-derived nitrogen inputs, the Towns of Oak Bluffs, Edgartown and the Martha's Vineyard Commission (MVC) undertook additional site-specific data collection that has served to support MEP's ecological assessment and modeling project.

The common focus of the Towns of Oak Bluffs/Edgartown - MVC efforts in the Sengekontacket Pond system has been to gather site-specific data on the current nitrogen related water quality throughout the pond system and determine its relationship to watershed nitrogen loads. This multi-year effort has provided the baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. The MEP effort builds upon the Water Quality Monitoring Program, and previous hydrodynamic and water quality analyses, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for each major sub-embayment. These critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater planning and nitrogen management alternatives development needed by the Towns of Oak Bluffs and Edgartown.

While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff and volunteers over many years, most notably from members of the Martha's Vineyard Commission, the Friends of Sengekontacket Pond and the Town of Oak Bluffs and Edgartown Shellfish Departments. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns of Oak Bluffs and Edgartown to work collaboratively to develop and evaluate the most cost effective nitrogen management alternatives to restore this valuable coastal resource which is currently being degraded by nitrogen overloading. It is important to note that the Sengekontacket Pond System and its associated watershed has been significantly altered by human activities over the past ~100 years. As a result, the present nitrogen "overloading" appears to result partly from alterations to its ecological systems. These alterations subsequently affect nitrogen loading within the watershed and influence the degree to which nitrogen loads impact the estuary. Therefore, restoration of this system should focus on managing nitrogen through both management of nitrogen loading within the watershed and restoration/management of processes which serve to lessen the amount or impact of nitrogen entering the estuary.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The nutrients are primarily related to changes in watershed land-use associated with increasing population within the coastal zone over the past half century. Many of Massachusetts' embayments have nutrient levels that are approaching or are currently over this assimilative capacity, which begins to cause declines in their ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities and the food chain which they support. At higher levels, nitrogen loading from surrounding watersheds causes aesthetic degradation and inhibits even recreational uses of coastal waters. In addition to nutrient related ecological declines, an increasing number of embayments are being closed to swimming, shellfishing and other activities as a result of bacterial contamination. While bacterial contamination does not generally degrade the habitat, it restricts human uses. However like nutrients, bacterial contamination is frequently related to changes in land-use as watersheds become more developed. The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the culture, economy, and tax base of Massachusetts's coastal communities.

The primary nutrient causing the increasing impairment of the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within Southeastern Massachusetts alone, almost all of the municipalities (as is the case with the Town of Edgartown) are grappling with

Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries.

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

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

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region’s coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the MASSDEP and municipalities with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an outline of an implementation plan. For this project, the MASSDEP recognizes that there are likely to be multiple ways to achieve the desired goals, some of which are more cost effective than others and therefore, it is extremely important for each town to further evaluate potential options suitable to their community. As such, MASSDEP will likely be recommending that specific activities and timelines be further evaluated and developed by the towns (sometimes jointly) through the Comprehensive Wastewater Management Planning process.

The MEP nitrogen threshold analysis includes site-specific habitat assessments and watershed/embayment modeling approaches to develop and assess various nitrogen management alternatives for meeting selected nitrogen goals supportive of restoration/protection of embayment health.

The major MEP nitrogen management goals are to:

- provide technical analysis and supporting documentation to towns as a basis for sound nutrient management decision making towards embayment restoration
- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 70 embayments in Southeastern MA

- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment's model "alive" to address future municipal needs.

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

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

The Linked Model has been applied for watershed nitrogen management in approximately 32 embayments throughout Southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach's greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options.

The Linked Watershed-Embayment Model when properly parameterized, calibrated and validated for a given embayment becomes a nitrogen management planning tool, which fully supports TMDL analysis. The Model facilitates the evaluation of nitrogen management alternatives relative to meeting water quality targets within a specific embayment. The Linked Watershed-Embayment Model also enables Towns to evaluate improvements in water quality relative to the associated cost. In addition, once a model is fully functional it can be "kept alive" and updated for continuing changes in land-use or embayment characteristics (at minimal cost). In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries.

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

- Watercolumn Monitoring - multi-year embayment nutrient sampling
- Hydrodynamics -

  - embayment bathymetry
  - site specific tidal record
  - current records (in complex systems only)
  - hydrodynamic model
- Watershed Nitrogen Loading
  - watershed delineation
  - stream flow (Q) and nitrogen load
  - land-use analysis (GIS)
  - watershed N model
- Embayment TMDL - Synthesis
  - linked Watershed-Embayment N Model
  - salinity surveys (for linked model validation)
  - rate of N recycling within embayment
  - D.O record
  - Macrophyte survey
  - Infaunal survey

I.2 NUTRIENT LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In sandy glacial outwash aquifers, such as in the watershed to the Sengekontacket Pond System, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer minerals (Weiskel and Howes 1992). Since even Martha's Vineyard and Cape Cod "rivers" are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems on Cape Cod (DeSimone and Howes 1998, Weiskel and Howes 1992, Smith *et al.* 1991) and Martha's Vineyard. The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). The estuarine reaches within the Sengekontacket Pond System follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

Nutrient related water quality decline represents one of the most serious threats to the ecological health of the nearshore coastal waters. Coastal embayments, because of their enclosed basins, shallow waters and large shoreline area, are generally the first indicators of nutrient pollution from terrestrial sources. By nature, these systems are highly productive environments, but nutrient over-enrichment of these systems worldwide is resulting in the loss of their aesthetic, economic and commercially valuable attributes.

Each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation. However, as loading increases a point is reached at which the capacity (termed assimilative capacity) is exceeded and nutrient related water quality degradation occurs. This point can be termed the "nutrient threshold" and in estuarine management this threshold sets the target nutrient level for restoration or protection. Because nearshore coastal

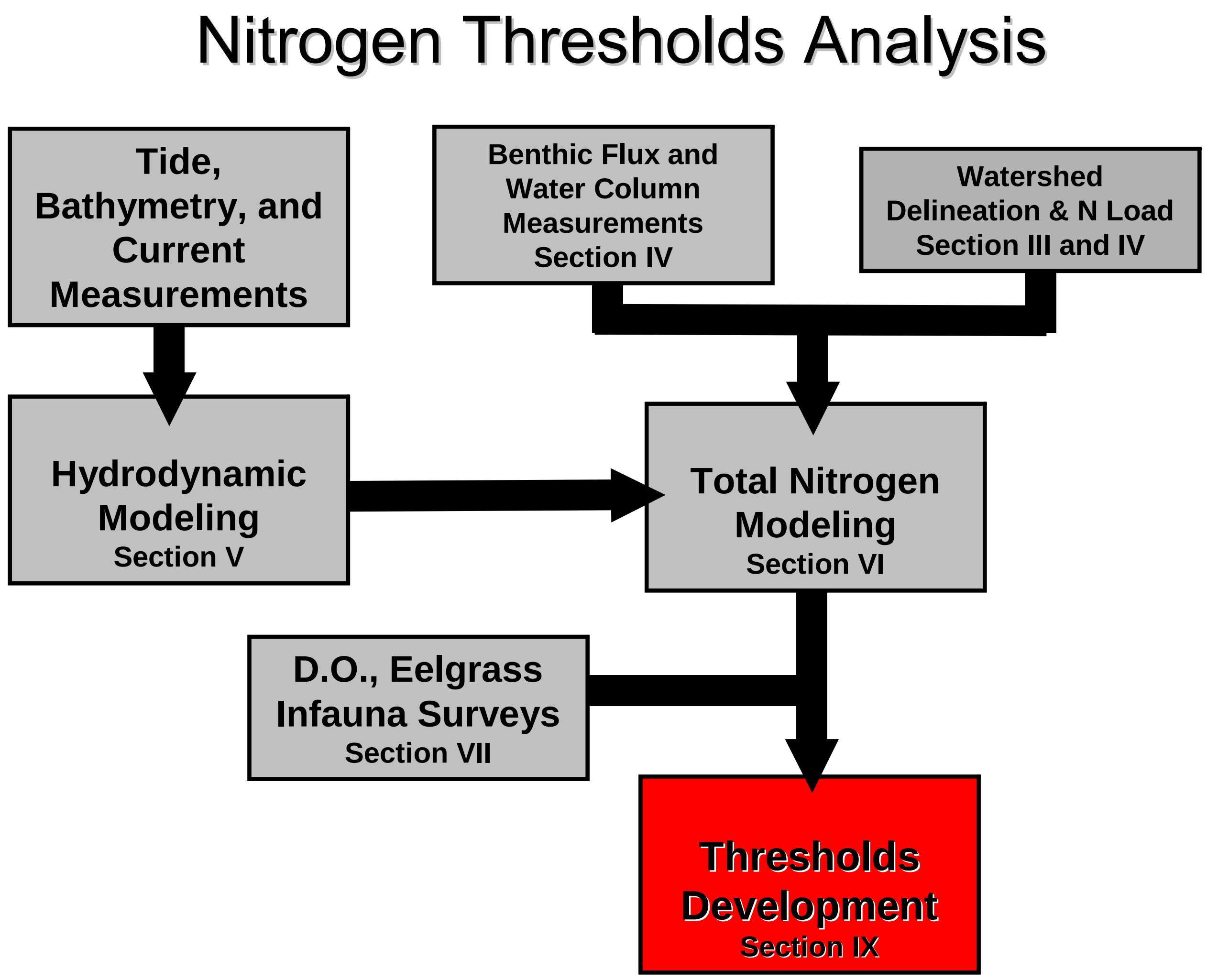

Figure I-3. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach salt ponds and embayments are the primary recipients of nutrients carried via surface and groundwater transport from terrestrial sources, it is clear that activities within the watershed, often miles from the 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 and the Islands have been the site of intensive efforts in this area (Eichner et al., 1998, Costa et al., 1992 and in press, Ramsey et al., 1995, Howes and Taylor, 1990, and the Falmouth Coastal Overlay Bylaw, MVC Water Quality Policy). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the “allowable N concentration increase” or “threshold nitrogen concentration” used in previous studies had a significant uncertainty due to the need for direct linkage of watershed and embayment models and site-specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout the Sengekontacket Pond System monitored by the Martha's Vineyard Commission and the Towns of Oak Bluffs and Edgartown. The Water Quality Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) was utilized to “tune” general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, almost all of the estuarine reaches within the Sengekontacket Pond System are near or beyond their ability to assimilate additional nutrients without impacting their ecological health. Nitrogen levels are elevated throughout this salt pond and eelgrass beds have declined over the past half century to a few residual patches, observed by the MEP Technical Team during the summer and of 2004. Nitrogen related habitat impairment within the Sengekontacket Pond Estuary shows a gradient of high to low moving from the inland reaches of the site such as Majors Cove and Trapps Pond to the inlets. The result is that nitrogen management of the primary basin and tributary coves of the Sengekontacket Pond system is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed “eutrophication” and in certain instances can occur naturally over long periods of time. When the nutrient loading is rapid and primarily from human activities leading to changes in a coastal watershed, nutrient enrichment of coastal waters is termed “cultural eutrophication”. Although the influence of human-induced changes has increased nitrogen loading to the systems and contributed to the degradation in ecological health, the Sengekontacket Pond basins are especially sensitive to nitrogen inputs because of the characteristics of tidal exchange with Vineyard / Nantucket Sound water. The quantitative role of the tidal restriction of this system at the secondary inlet at the northern end of the pond was also considered in the MEP nutrient threshold analysis. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a “pristine” system.

I.3 WATER QUALITY MODELING

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

The MEP water quality evaluation examined the potential impacts of nitrogen loading into the Sengekontacket Pond System, including the tributary sub-embayments of Majors Cove and Trapps Pond. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents at the two inlets to the pond system and water elevations was employed for the hydrodynamic analysis of the entire Sengekontacket Pond system. Once the hydrodynamic properties of each component of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon MEP refined (working with the USGS) watershed delineations originally developed by Earth Tech. Almost all nitrogen entering the Sengekontacket Pond System is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Vineyard / Nantucket Sound source waters and throughout the Sengekontacket Pond system were taken from the Town of Oak Bluffs-Edgartown/MVC Water Quality Monitoring Program (a coordinated effort between the Towns of Oak Bluffs, Edgartown, the Martha's Vineyard Commission and the Coastal Systems Program at SMAST). Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of the System (1995, 1996 and 2003-2009) were used to calibrate and validate the water quality model (under existing loading conditions).

I.4 REPORT DESCRIPTION

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

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

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

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

A number of studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Sengekontacket Pond System over the past two to three decades.

Distribution of Fecal Coliform Bacteria in Surface Waters of Sengekontacket Pond and Management Implications (1991) – This report (Interim Report #1) was prepared by Arthur Gaines, from the Marine Policy Center of the Woods Hole Oceanographic Institution. The report was developed by Dr. Gaines for the Friends of Sengekontacket. While the report is not directly pertinent to the issue of habitat impairment resulting from nutrient over-enrichment of the Sengekontacket Pond system, it does offer some insights into potential sources of contamination. Often times, these sources of contamination also have associated nutrient implications for the receiving water, particularly in the context of septic systems as well as avian/wildlife populations. In this report Gaines determined that highest bacterial counts were observed in the warm summer months and were located primarily in the coves along the southwest margin of the system, potentially as a result of slightly lower salinities in these areas as well as poor flushing. At the time of the study, no human sources of fecal coliform bacteria were found as there were no sewage outfalls to the pond, there was no cruising boat pressure such as live-boards and no evidence of failing septic systems. As such, Gaines concludes that the high bacterial counts are likely due to warm blooded wildlife living in the watershed and near shore areas to the pond.

Managing Domestic Wastewater at the Coast: A Natural Systems Assessment of Sengekontacket Pond, Martha's Vineyard (1995). - This report was prepared by Arthur Gaines, from the Marine Policy Center of the Woods Hole Oceanographic Institution. The report was developed by Dr. Gaines for the Friends of Sengekontacket. While the report is out dated, it was directly pertinent to the issue of habitat impairment resulting from nutrient over-enrichment of the Sengekontacket Pond system and did offer a reference point for the level of nutrient loading to the system in 1994 and a relation to the habitat quality at that point in time. At the time of the study, the main impetus for conducting the analysis was the potential siting of a wastewater treatment facility in the Sengekontacket Watershed. In order to establish the nutrient status of the pond in 1994, intensive sampling was conducted over a one week period in July to capture a period of warmest water temperatures and specific biological activity. Samples were obtained from stations in Major's Cove as well as the inlet and were assayed for dissolved nutrients, namely nitrate, nitrite, ammonia, phosphate and silica. Particulate material from inlet samples was analyzed for chlorophyll-a, carbon and nitrogen. Primary productivity and oxygen demand estimates were also undertaken in Majors Cove using light-dark bottle techniques as well as monitoring diurnal oxygen levels in Major's Cove using instrumentation. Based on the results, Gaines concluded that in 1994, the Sengekontacket Pond system received a relatively low nutrient load from its watershed and had low primary productivity compared to other estuaries on the island. Primary productivity and respiration in Sengekontacket Pond was lower than for other ponds on the island and during the July observation period in the summer of 1994, daily net primary productivity was negative. Additionally, standing stock of submerged aquatic vegetation during the observation period was considered low and it was concluded based on the one week sampling that chlorophyll-a during the observation period was being imported to Sengekontacket Pond from Nantucket Sound. At the time of the observations in 1994, it was concluded that pond water quality was high and that flushing was very strong. Furthermore, it was determined that should additional nitrogen loads be introduced to the system, because the nitrogen to phosphorous ratio was estimated between 2 and 3 (indicating nitrogen limitation), this increased loading would result in increased algal growth. The study also undertakes land use analysis of the watershed in order to estimate nitrogen loading to the system. While the analysis is out dated, it still serves as a historical frame of reference for assessing how conditions have changed both in the watershed and in the pond.

Management Guidance for Sengekontacket Pond (1998) – This report was developed in fulfillment (at the time) of a recommendation within the Martha's Vineyard Regional Island Plan. The Guidance document was prepared by the Martha's Vineyard Commission and the Principal author was Jo-Ann Taylor, Coastal Planner. The guidance report included an analysis of existing data and made management recommendations relative to water quality, inlet management, user conflicts and monitoring. While offering a useful description of watershed characteristics at the time, the report focuses on specific potential contaminants to the

Sengekontacket Pond system, specifically nutrients, along with pathogens and run-off. Of particular interest is the statement that at the time of the analysis, based on available data, nutrient loading did not appear to be of particular concern as loading estimates to the pond seemed relatively in balance with the assimilative capacity of the system. However, the statement was qualified in that should nutrient loading increase to beyond the level observed in 1997-98 and circulation and flushing decrease, it could become a mechanism for impairment of this coastal resource. In that light, the report does make recommendations regarding both structural and non-structural mechanisms for addressing the potential problem of nutrient enrichment, such as establishing undeveloped buffer zones in the immediate vicinity of the pond shore and inlet management.

The report also clearly identifies that nutrient source reduction is critical to the ultimate management of the resource and that this requires a priori the accurate determination of the systems nitrogen carrying capacity, also known as the systems assimilative capacity, before the signs and symptoms make it obvious that there is a nitrogen over-enrichment problem. Based on the Buzzards Bay Project method for calculating the nitrogen loading limit for an estuary, the authors determined that the theoretical limit for nitrogen loading to Sengekontacket Pond would be 281,561 kg/yr, significantly higher than the "present" load of 10,120 kg/yr as calculated by Gaines in 1995 and referenced in this 1998 report. While a theoretical limit was established in 1998, it is clearly orders of magnitude greater than what the MEP has been finding to be levels of nutrient loading that would be restorative of estuarine systems similar in size and structure as Sengekontacket Pond. The report does, however, serve as a valuable back drop to this next generation analysis being completed by the MEP. Equally valuable is that the report stresses the need for building on early monitoring to establish a solid water quality baseline, utilizing citizenry to do so in order to reduce costs and keep the public informed and engaged and conduct regular updates to the eelgrass inventory every five years in order to monitor decline and potential increase of algae, particularly in the coves. The MEP analysis aims to further advance sound management of the Sengekontacket Pond system and has considered historical findings as presented in this report.

***A Survey of the Eelgrass Beds of Sengekontacket and Farm Ponds, Edgartown and Oak Bluffs, Massachusetts, (1998)* -** Kara Hempy (intern) under the supervision of William Wilcox, from the Martha's Vineyard Commission undertook this analysis of eelgrass presence and distribution in Sengekontacket Pond. The report, completed by Hempy and Wilcox, offers updated data on eelgrass in the ponds and reports on an attempt to transplant eelgrass into Sengekontacket Pond. The study employed straightforward methods and the report offers good analysis of transplanting efforts. The survey of eelgrass was conducted by boat transects and did not include aerial photography. The results indicated that eelgrass was identified in Major's Cove and was found to be dense in Trapps Pond. Sign of wasting disease (a plant pathogen suspected in the regional decline of eelgrass) was identified. The transplants failed; spider crabs were suspected to contribute to the failure. The report provides a solid update to the eelgrass mapping in Major's Cove and adds baseline data on Trapps Pond.

***Nutrient Loading and Management Strategies at Sengekontacket Pond (1999)* -** Arthur Gaines, from the Marine Policy Center of the Woods Hole Oceanographic Institution developed this report for the Friends of Sengekontacket. This study offers insight into the state of Sengekontacket Pond in 1999 as well as potential management steps. He reiterates his conclusions from previous studies that Sengekontacket Pond is neither eutrophic nor over-enriched and that the pond is "healthy," but continues to emphasize that nitrogen input is the central pond management issue. Original data from nutrient enrichment studies suggest that the Pond would not suffer immediate adverse impacts from additional nitrogen inputs. The author recommends pursuit of an adaptive management plan and offers a broad list of possible actions for Friends of Sengekontacket, from local education to motivating a nitrogen discharge quota system, which, although complex, has been implemented on parts of Cape Cod.

Impacts of Dredging on Sengekontacket Pond (2000) – Arthur Gaines, from the Marine Policy Center of the Woods Hole Oceanographic Institution developed this report for the Friends of Sengekontacket. This report offers general thoughts on the potential impacts of the 1997 dredging activity in Sengekontacket Pond. It offers a detailed history of the dredging project with bathymetric maps of the borrow site before and after dredging. The author updated tidal studies of the pond, but suggests that additional data are needed to comment on changes due to dredging.

Report on tidal exchange between Sengekontacket and Trapps Ponds. Martha's Vineyard Commission, Oak Bluffs (2002) - In this report, William Wilcox from the MVC uses new data to investigate the potential tidal restriction into Trapps Pond. After monitoring tide height on both sides of the Trapps Pond culvert, Wilcox concludes that the culvert size is inadequate to pass the tidal prism that is available at the Sengekontacket Pond gage through to the Trapps Pond side of the culvert. The report further concludes that increased tidal exchange would likely result from enlarging size of culvert, and that such increased exchange would tend to increase flushing of nutrients out of Trapps Pond. The presence of epiphytes on eelgrass within Trapps Pond is presented as evidence of high nutrient loading within Trapps Pond. One of the recommendations made in the study is that before pursuing an enlarged culvert, additional work must be undertaken that investigates the potential impacts of increased flow to Trapps Pond, such as: flooding on the margins of Trapps Pond; erosion of the channel by increased flow; and increasing salinity at Trapps Pond margins. Other studies need to be completed to determine whether increasing flow will contribute to flushing of Upper Trapps Pond and to assure that any culvert design meets the needs of anadramous fish.

Identifying Sources of Fecal Contamination in the Salt Ponds of Martha's Vineyard 2007 – This examination of bacterial contamination in salt ponds of Martha's Vineyard, inclusive of Sengekontacket Pond, was conducted by Dr. Stephen Jones at the University of New Hampshire Jackson Estuarine Laboratory. In this study, microbial source tracking was undertaken using cultures of fecal indicator bacteria (in this case *E. coli*) isolates in order to identify the most significant contaminant source species. Ribotyping analysis was completed for source species identification and it was determined that significant bird sources and localized dog sources are responsible for bacterial contamination in Sengekontacket Pond as well as the three other ponds included in the study, one of which was Farm Pond. The pertinent aspects of the overall analysis and results were taken into consideration by the MEP as a historical back drop for the current analysis.

MVC/Town of Oak Bluffs and Edgartown Water Quality Monitoring Program (2002-2007) - The Martha's Vineyard Commission partnered with SMAST-Coastal Systems Program scientists in 2002 to develop and implement a nutrient related water quality monitoring program of the estuaries of Martha's Vineyard inclusive of Sengekontacket Pond in the Town of Oak Bluffs and Edgartown. The Martha's Vineyard Commission working with the Town of Oak Bluffs and Edgartown Shellfish Departments coordinated and executed the water quality surveys of the Sengekontacket Pond System. For Sengekontacket Pond as well as the other estuarine systems of Martha's Vineyard, the focus of the effort has been to gather site-specific data on the current nitrogen related water quality throughout the estuarine reach of the system to support assessments of habitat health. This baseline water quality data are a prerequisite to entry into the MEP and the conduct of its Linked Watershed-Embayment Approach. Water quality monitoring of the Sengekontacket Pond System has been a coordinated effort between the MVC, the towns and the Coastal Systems Program at SMAST-UMD. The water quality monitoring program was initiated in 2002 with support from the Massachusetts 604B Grant Program and continued uninterrupted through the summer of 2007. Throughout the water quality monitoring period, sampling was undertaken between 4 and 6 times per summer between the months of June and September. The MVC/Town based Water Quality Monitoring Program for Sengekontacket Pond developed the baseline data from sampling stations distributed throughout the main tidal channel and the tributary sub-basin of Major's Cove as well as water flowing out of Trapps Pond (Figure II-1). As remediation plans for this and other various systems on Martha's Vineyard are implemented throughout the towns, monitoring will have to be resumed or continued to provide quantitative information to the towns relative to the efficacy of remediation efforts.

Implementation of the MEP Linked Watershed-Embayment Approach incorporates the quantitative water column nitrogen data (2002-2007) gathered by the Monitoring Program and watershed and embayment data collected by MEP staff. The MEP effort also builds upon previous watershed delineation and land-use analyses as well as historical eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Sengekontacket Pond Estuarine System. The MEP has incorporated all appropriate data from previous studies to enhance the determination of nitrogen thresholds for the Sengekontacket Pond System and to reduce costs of restoration for the Towns of Oak Bluffs and Edgartown.

Regulatory Assessments of Sengekontacket Pond Resources - The Sengekontacket Pond Estuary contains a variety of natural resources of value to the citizens of Oak Bluffs and Edgartown as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP gathers the available information on these resources as part of its assessment, and presents them here (Figures II-2 through II-6) for reference by those providing stewardship for this estuary. For the Sengekontacket Pond Estuary these include:

- Mouth of River designation - MassDEP (Figures II-2a and II-2b)
- Designated Shellfish Growing Area – MassDMF (Figure II-3)
- Shellfish Suitability Areas - MassDMF (Figure II-4)
- Anadromous Fish Runs - MassDMF (Figure II-5)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-6)

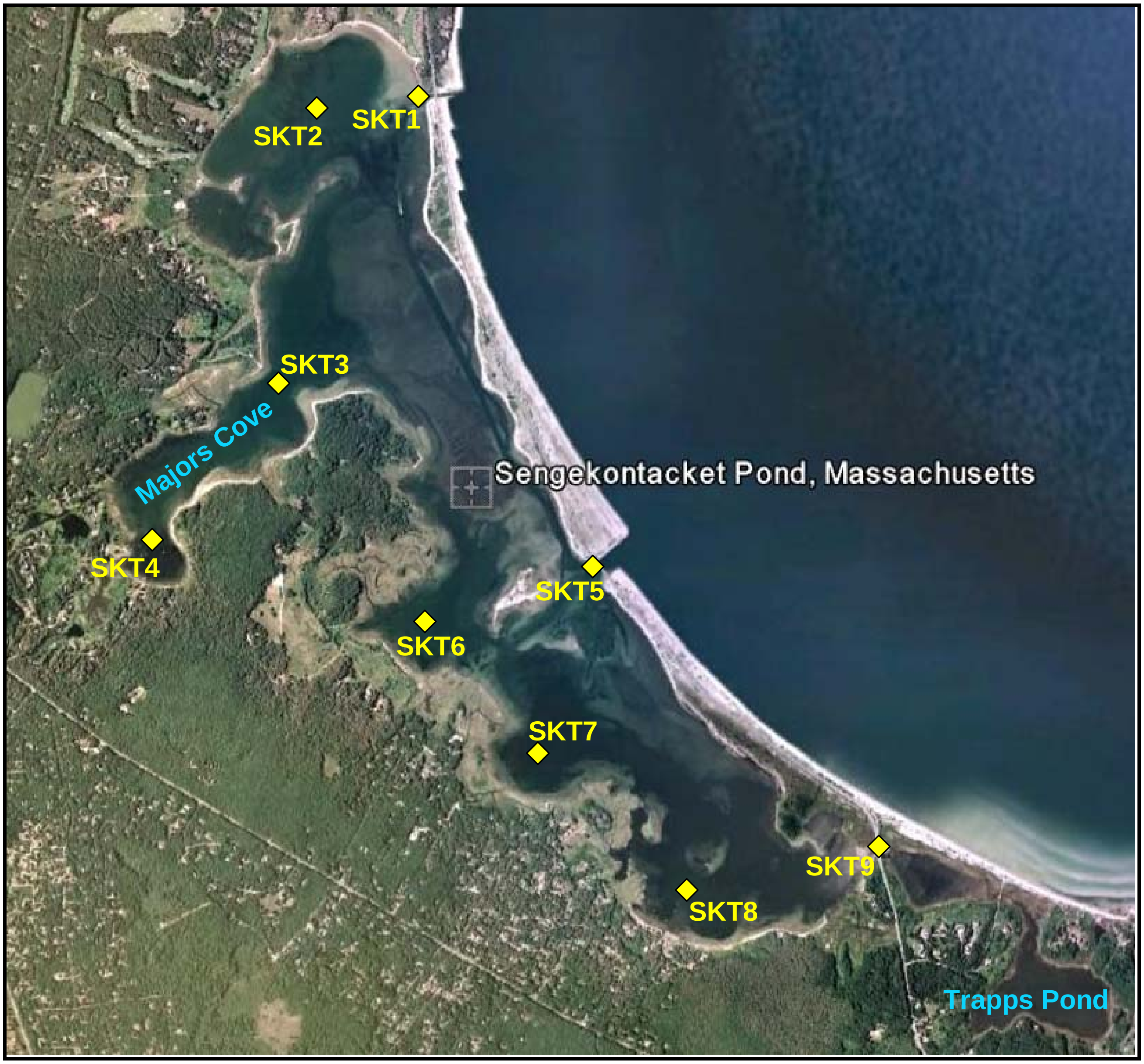

Figure II-1. MVC/Town of Oak Bluffs/Town of Edgartown Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the MVC/SMAST/Town and volunteers.

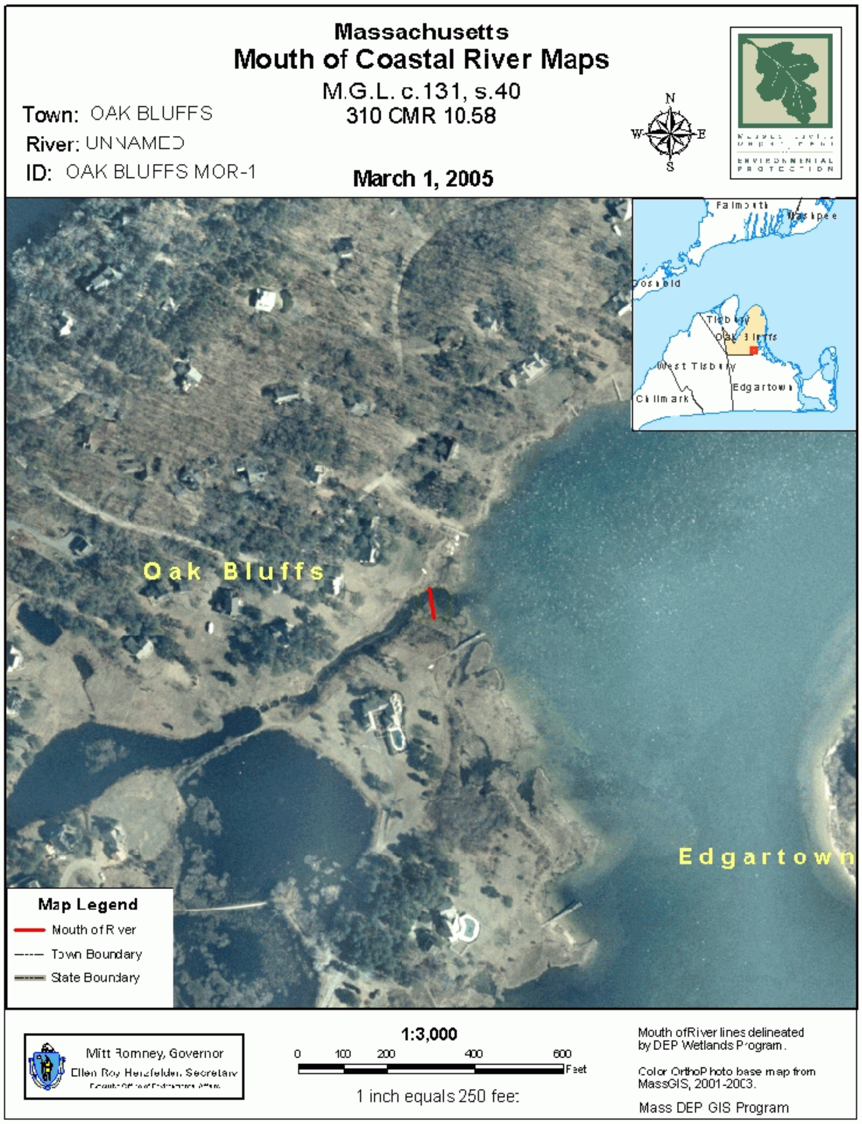

Figure II-2a. Regulatory designation for the mouth of “River” line under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

Figure II-2b. Regulatory designation for the mouth of "River" line under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

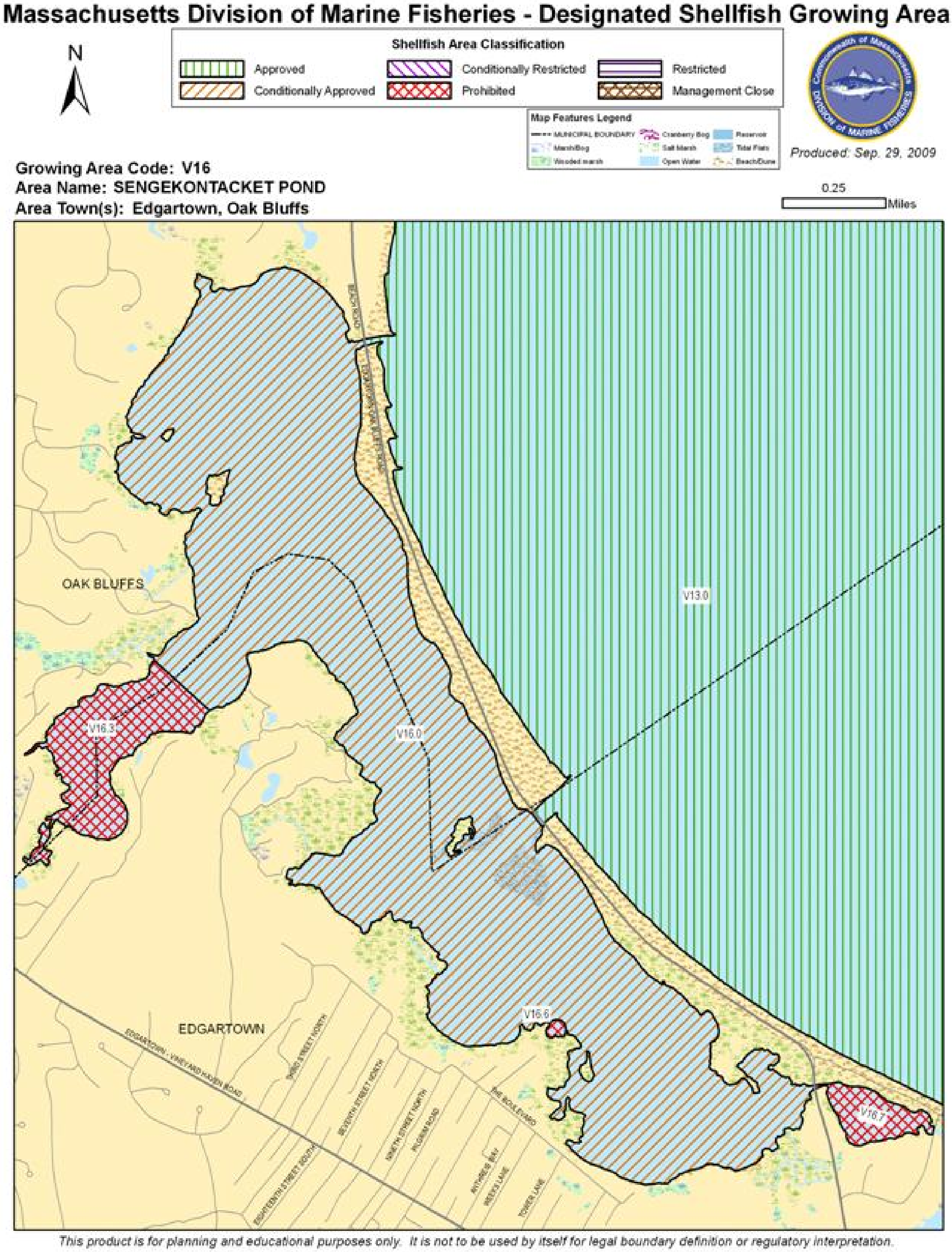

Figure II-3. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

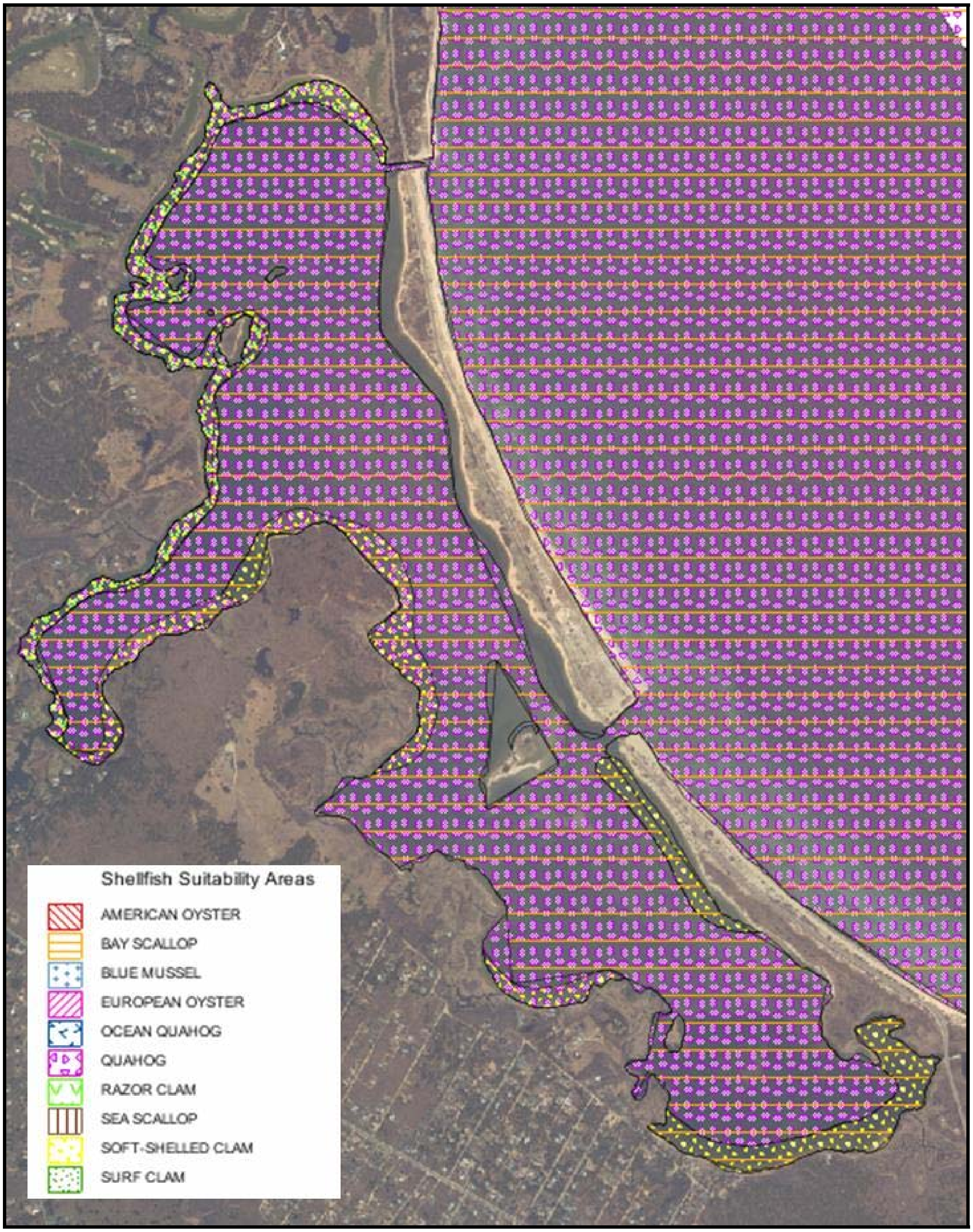

Figure II-4 Location of shellfish suitability areas within the Sengekontacket Pond Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

Figure II-5 Anadromous fish runs within the Sengekontacket Pond and Trapps Pond Estuary as determined by Mass Division of Marine Fisheries. The red diamonds show areas where fish were observed.

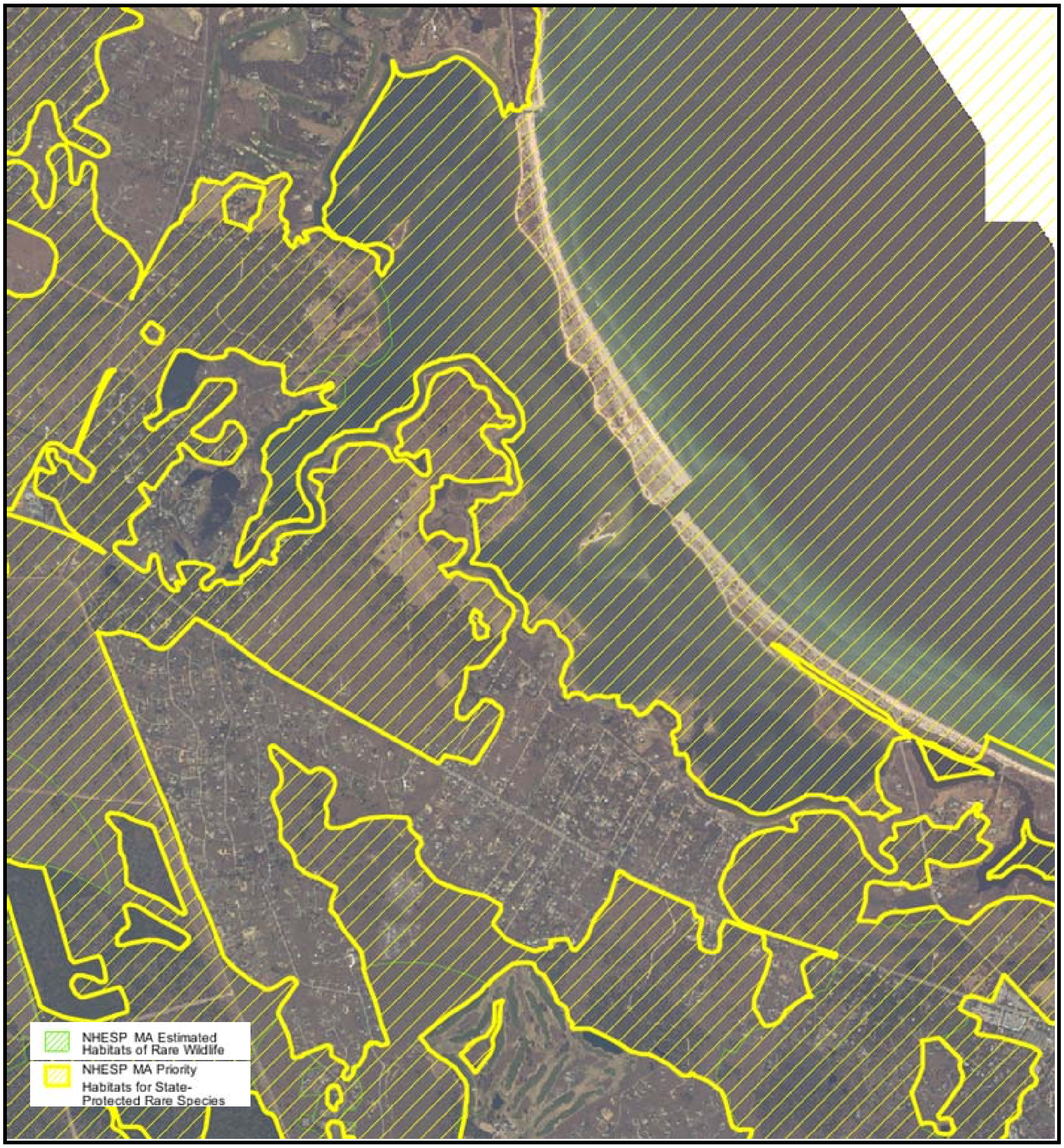

Figure II-6. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Sengekontacket and Trapps Pond Estuary as determined by - NHESP.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

Martha's Vineyard Island is located along the southern edge of late Wisconsinan glaciation (Oldale and Barlow, 1986). As such, the geology of the island is largely composed of glacial outwash plain and moraine with reworking of these deposits by the ocean that has occurred since the retreat of the glaciers. The island was located between the Cape Cod Bay and Buzzards Bay lobes of the Laurentide ice sheet. As such, the areas where the glacial ice lobes moved back and forth with warming and cooling of the climate are moraine areas and these moraines are located along the Nantucket Sound/eastern and Vineyard Sound/western sides of the island. These moraines generally consist of unsorted sand, clay, silt, till, and gravel with the western moraine having the more complex geology (*i.e.*, composed of thrust-faulted coastal plain sediments interbedded with clay, till, sand, silt and gravel) and the eastern moraine having more permeable materials overlying poorly sorted clay, silt, and till (Delaney, 1980). The middle portion of the island is generally outwash plain and is composed of stratified sands and gravel deposited by glacial meltwater.

The relatively porous deposits that comprise most of the Vineyard outwash plain and the eastern moraine create a hydrologic environment nearly completely lacking streams 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 a stream and the portion of the groundwater system that discharges directly into an estuary as groundwater seepage. In the Sengekontacket Pond watershed, nearly all freshwater watershed inputs to the estuary are via groundwater.

Sengekontacket Pond and its watershed are mostly located within the eastern moraine with the westernmost portions of the watershed within the outwash plan. The groundwater system in the eastern moraine has generally been characterized as nearly as permeable as the outwash plain. Additionally, the 1977 United States Geological Survey (USGS) regional water table map shows northern groundwater flow lines from the western moraine toward the eastern coast that seem uninfluenced by the moraine (Delaney, 1980). This is consistent with the fact that public supply well pump tests and modeling produce Zone 2 areas that are largely unaffected by the geology of the two areas. In 1991, the USGS developed another regional water table map, which generally showed the same water table contours (Masterson and Barlow, 1996). Masterson and Barlow constructed a regional two-dimensional, finite-difference flow model that could be used to calculate drawdowns in groundwater levels due to pumping of public water supply wells, but could not be calibrated against actual water level readings. These USGS characterizations of the geology, including the installation of numerous long-term monitoring wells, over the last few decades have provided the basis for subsequent activities, including the delineation of estuary watersheds. In 1994, Whitman and Howard produced a groundwater model with a domain that covered Martha's Vineyard eastern moraine and the outwash plain; this model was based on the publicly available USGS MODFLOW three-dimensional, finite difference groundwater model code. In 1995, Gaines produced a watershed for Sengekontacket Pond based on the water table contours. In 1999, Earth Tech updated the 1994 Whitman and Howard regional model and used an associated model to delineate watersheds. These watersheds were adopted by the Martha's Vineyard Commission (MVC) and are used in the MVC's guidance for the review of Developments of Regional Impact and as guidance to the towns of the Martha's Vineyard.

The MEP Technical team members include groundwater modeling staff from the United States Geological Survey (USGS). These USGS modelers were central to the development of the groundwater modeling/watershed delineation approach used for the MEP and are regularly consulted regarding MEP watershed delineations. USGS and SMAST scientists reviewed the Martha's Vineyard regional groundwater model and completed a number of updates based on previous reviews completed for the MEP assessment of Edgartown Great Pond (Howes *et al.*, 2008). Generally these reviews found that the Martha's Vineyard Commission watersheds are an adequate basis for MEP analysis.

III.2 SENGEKONTACKET POND CONTRIBUTORY AREAS

MEP technical staff reviewed the subregional groundwater model originally prepared by Whitman Howard (1994) and subsequently updated by Earth Tech. This model organized much of the historic USGS geologic data collected on Martha's Vineyard and provided a satisfactory basis for incorporating the MEP refinements necessary to complete the Sengekontacket Pond watershed delineation.

MEP technical staff revised the model grid to match orthophotographs of the island, which resulted in a model grid with 126 rows oriented southwest and 167 columns oriented southeast. Hydraulic conductivities were reworked to match the revised grid. Outputs from the revised model were compared with water table elevations generated for previously MassDEP-approved Zone II drinking water well contributing area delineations and the match was acceptable. Technical staff then used this model to define the watershed or contributing area to Sengekontacket Pond and its subestuaries. The Sengekontacket Pond watershed is situated along the eastern edge of Martha's Vineyard and is bounded by the Atlantic Ocean/Nantucket Sound to the east (Figure III-1).

MEP staff utilized the Sengekontacket Pond watershed to develop daily discharge volumes for various sub-watersheds as calculated from the watershed areas and an island-specific recharge rate. In order to develop the groundwater discharge volumes, MEP staff determined a recharge rate of 28.7 inches per year for Martha's Vineyard. This recharge rate estimate was largely based on review of the relationship between recharge and precipitation rates used on Cape Cod. In the preparation of the Cape Cod groundwater models, the USGS used a recharge rate of 27.25 in/yr for calibration of the groundwater models to match measured water levels (Walter and Whealan, 2005). The Cape Cod recharge rate is 61% of the estimated 44.5 in/yr of precipitation on the Cape. Precipitation data collected by the National Weather Service at Edgartown since 1947 has an average over the last 20 years of 46.9 in/yr (http://www.mass.gov/dcr/waterSupply/rainfall/precipdb.htm). If the Cape Cod relationship between precipitation and recharge is applied to the average Martha's Vineyard precipitation rate, the estimated recharge rate on Martha's Vineyard is 28.7 in/yr. This rate was used to estimate groundwater flow to Sengekontacket Pond and its various subwatersheds (Table III-1). The discharge volumes developed for the subwatersheds were used to assist in the salinity calibration of the tidal hydrodynamic models. The overall estimated groundwater flow into Sengekontacket Pond from the MEP delineated watershed is 35,883 m3/d.

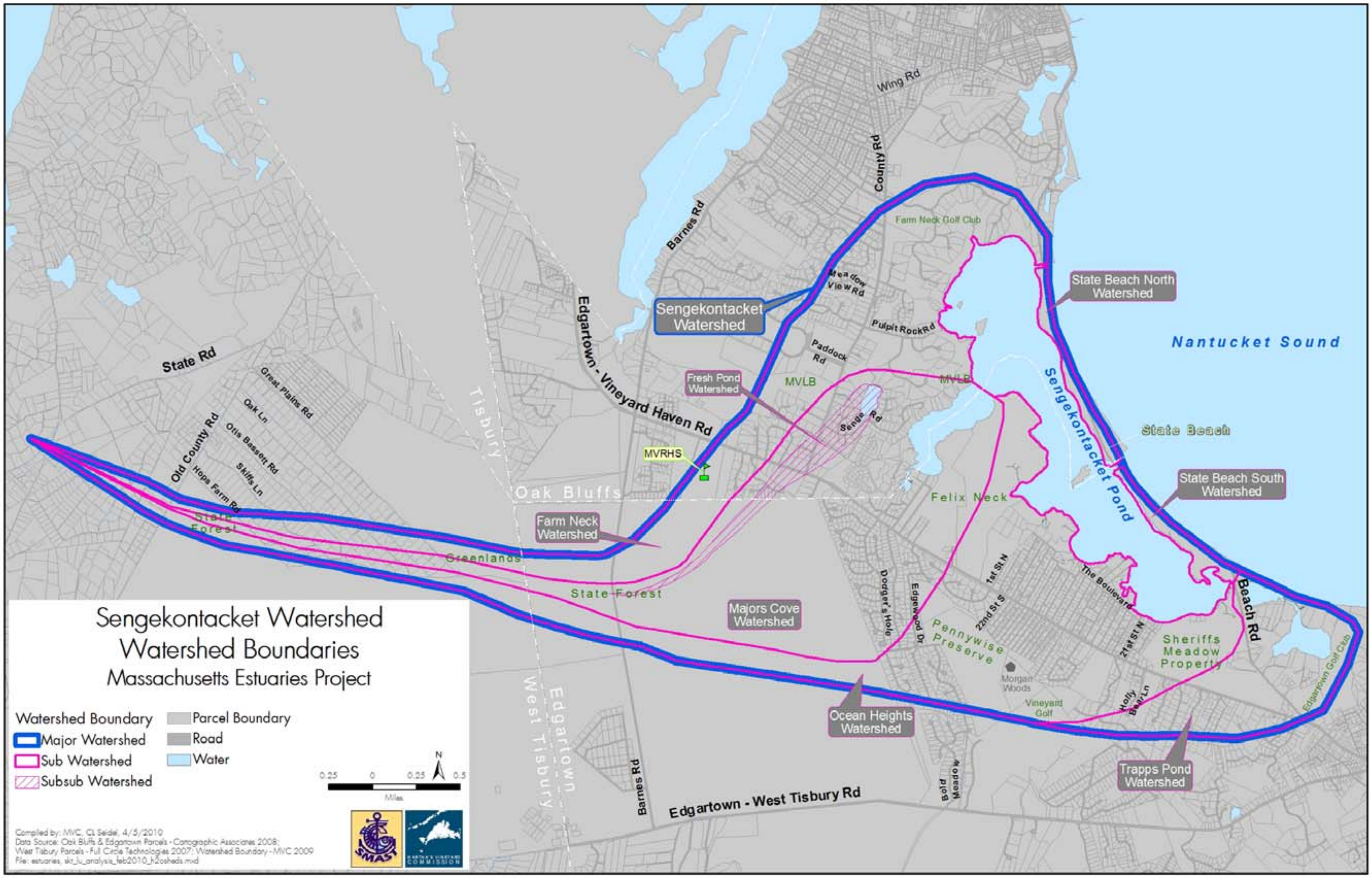

Figure III-1. Watershed and sub-watershed delineations for the Sengekontacket Pond estuary system. Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI).

The area and estimated discharge for the MEP watershed delineation are similar to previous delineations. Gaines (1995) estimated a 4,900-acre groundwater watershed to Sengekontacket Pond based on Delaney's (1980) water table map. A watershed delineation based on Whitman and Howard's (1994) modeled water table map has a watershed area of 4,472 acres (MVC, 2005). Given the model grid refinements completed by the MEP Technical Team, led in this effort by USGS staff, MEP Technical Team staff are highly confident that the delineation in Figure III-1 is accurate and an appropriate basis for completion of the linked watershed-embayment model for Sengekontacket Pond.

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

Watershed	**Watershed #**	**Watershed Area (acres)**	**Discharge**	
			m^3/day	**ft^3/day**
Farm Neck	1	1,110	8,969	316,744
Majors	2	1,356	10,962	387,127
Ocean Heights	3	1,382	11,168	394,409
Trapp's Pond	4	395	3,192	112,715
Fresh Pond	5	112	903	31,882
State Beach	6	85	688	24,310
TOTAL		4,440	35,883	1,267,187

NOTE: Discharge rates are based on 28.7 inches per year of recharge.

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

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

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

The MEP Technical Team worked with the Martha's Vineyard Commission (MVC) staff to develop the watershed nitrogen loads to the Sengekontacket Pond Estuary. This effort led to the identification of watershed nitrogen sources and the development of nitrogen-loading rates (Section IV.1) to the watershed and to the tidal waters of Sengekontacket Pond. The Sengekontacket Pond watershed was sub-divided into six (6) subwatersheds, defining the contributing areas to each of the major component basins of the Sengekontacket Pond Estuary (Chapter III).

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other in-depth 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 Sengekontacket Pond embayment system, the model used MVC-supplied land-use data transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as water use data provided by the Oak Bluffs Water District and Edgartown Water Department). 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 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. Attenuation through the ponds is conservatively assumed to equal 50% unless available monitoring and pond physical data is reliable enough to calculate a pond-specific attenuation factor. Attenuation through streams is usually based on site-specific study of streamflow. In the Sengekontacket Pond watershed, there are no delineated watersheds to streams and the only pond with a delineated watershed is Fresh Pond. Surface water attenuation in Fresh Pond is discussed in the freshwater pond section. Other, smaller aquatic features within the watershed to Sengekontacket Pond do not have separate watersheds delineated and, thus they are not explicitly included in the watershed analysis. If these small features were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (~10%) overestimated given the distribution of nitrogen sources and these features within the watershed.

Based upon the evaluation of the watershed and the various estimated sources of nitrogen, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the subwatersheds that directly discharge groundwater to the estuary without flowing through an interim pond or stream measuring point. Reductions in subwatershed nitrogen loads were made to account for natural attenuation in ponds or streams as appropriate. Internal nitrogen recycling was also determined throughout the tidal reaches of the Sengekontacket Pond Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Martha’s Vineyard Commission (MVC) staff, with the guidance of Estuaries Project staff, combined digital parcel and tax assessors’ data from the MVC Geographic Information Systems Department. Digital parcels and land use/assessors data are from 2008. These land use databases contain traditional information regarding land use classifications (MADOR, 2002) plus additional information developed by the MVC.

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

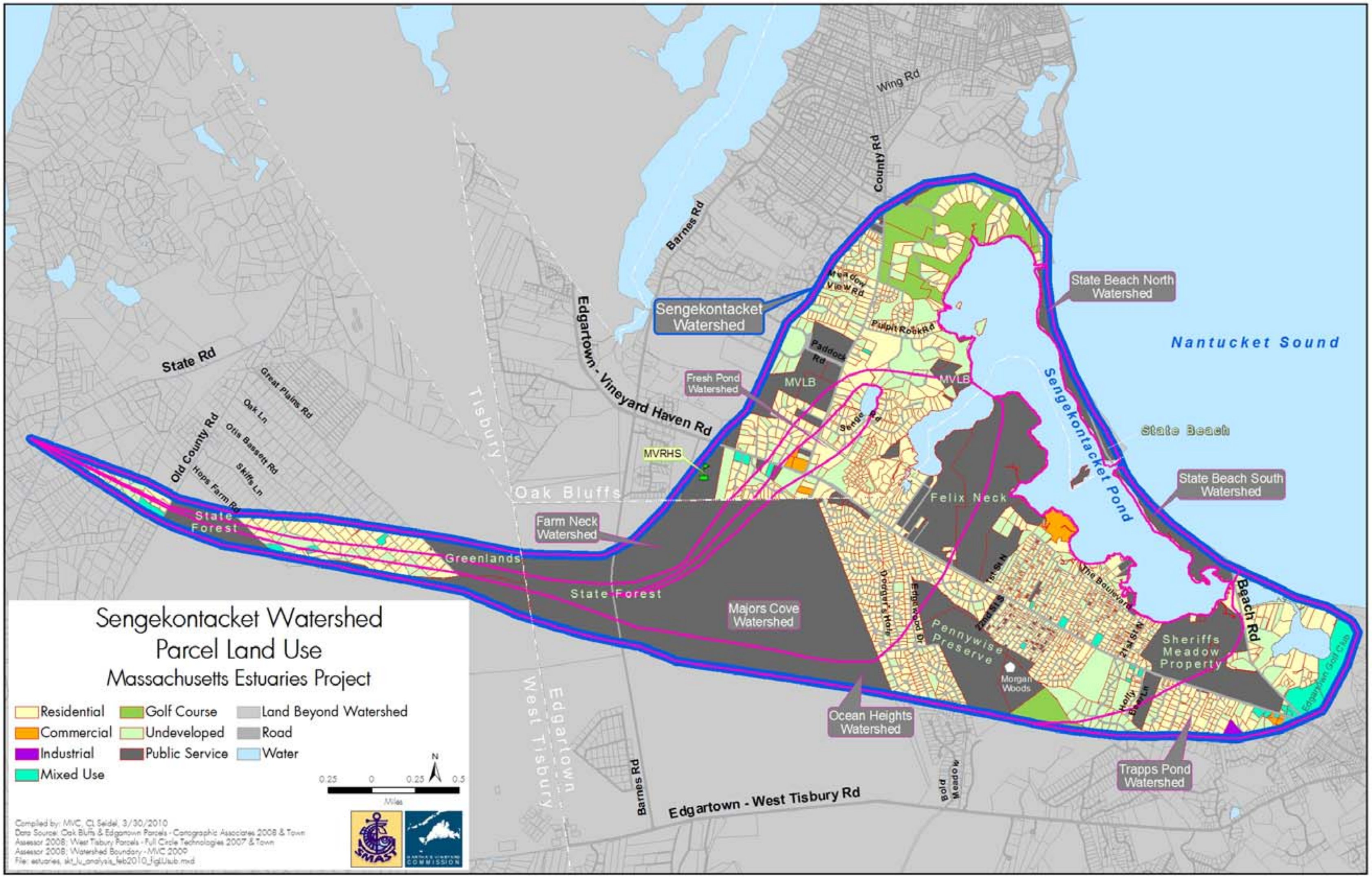

Figure IV-1. Land-use in the Sengekontacket Pond watershed. Watershed extends over three towns: Edgartown, Oak Bluffs, and West Tisbury. Land use classifications are based on assessors' records provided by the towns.

In the overall Sengekontacket Pond System watershed, the predominant land use based on area is public service (government owned lands, roads, and rights-of-way), which accounts for 52% of the overall watershed area; residential is the second highest percentage of the system watershed at 28% (Figure IV-2). However, 65% of the parcels in the system watershed are classified as residential. Single-family residences (MADOR land use code 101) are 87% of the residential parcels and 79% of the residential land area. Public service land uses are the dominant land use category in four of the six individual subwatersheds and the overall system watershed. Residential land uses are the dominant land use in the two remaining subwatersheds: Trapp's Pond and Fresh Pond. Undeveloped parcels are generally the third highest land use area classification in the subwatersheds. Overall, undeveloped land uses account for 14% of the entire Sengekontacket Pond watershed area, while golf course properties account for the next highest percentage at 5%.

In all the subwatershed groupings shown in Figure IV-2, residential parcels are the dominant parcel type in all subwatersheds except State Beach, ranging between 56% and 81% of all parcels in these subwatersheds and 65% of all parcels in the whole Sengekontacket Pond system watershed. Single-family residences (MassDOR land use code 101) are 77% to 91% of residential parcels in these same individual subwatersheds and 87% of the residential parcels throughout the whole Sengekontacket Pond system watershed. Single-family residences are also 79% of the residential land use areas in the whole system watershed.

In order to estimate wastewater flows, MEP staff generally work with municipal or water supplier partners in the study watershed to obtain parcel-by-parcel water use information. With this in mind, MVC staff contacted both the Edgartown Water Department (EWD) and the Oak Bluffs Water District and obtained water use information for properties in the Sengekontacket Pond watershed. Both water suppliers provided water use for four years (2003-2006). Review of this data found that 853 of the parcels in the Sengekontacket Pond system watershed have water use accounts, while 634 developed parcels do not have accounts. MVC staff determined that the average water use among parcels with water use accounts in the Edgartown portion of the Sengekontacket Pond watershed is 76,380 gallons per year, while parcels with water use accounts average 82,900 gallons per year in the Oak Bluffs portion of the watershed. Average water uses were determined by land use classification, town, and subwatershed. For single-family residences (land use code 101), average water use generally had a range of 61,300 to 90,400 gallons per year or 168 to 248 gallons per day. Average water use based on watershed and land use was assigned to developed properties without water use accounts. Water use is used as a proxy for wastewater generation from septic systems on all developed properties in the Sengekontacket Pond watershed. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the average water-use, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2).

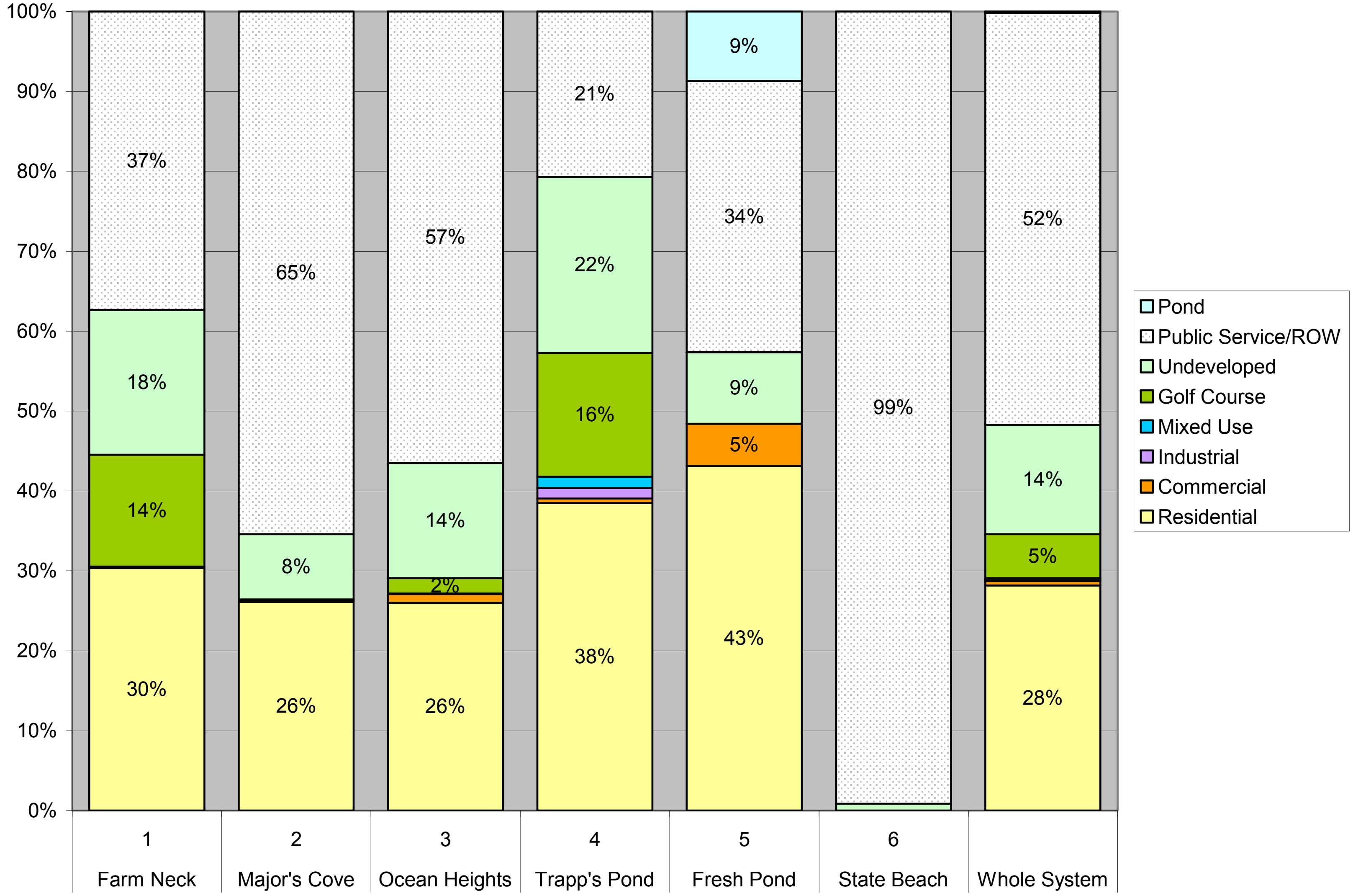

Figure IV-2. Distribution of land-uses within the subwatersheds and whole watershed to Sengekontacket Pond. Only percentages greater than or equal to 2% are shown. Land use categories are based on Massachusetts DOR (2008) classifications.

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts, decennial census data yields accurate estimates of total population only in selected watersheds. To correct for this uncertainty and more accurately assess current nitrogen loads, the MEP employs a water-use approach. The water-use approach is generally applied on a parcel-by-parcel basis within a watershed, where annual water meter data is linked to assessor's 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 for an effective N Loading Coefficient (consumptive use times N concentration) of 23.63, to convert water (per volume) to nitrogen load (N mass). This coefficient uses a per capita nitrogen load of 2.1 kg N person-yr^{-1} and is based upon direct measurements and corrects for changes in concentration that result from per capita shifts in water-use (e.g. due to installing low plumbing fixtures or high versus low irrigation usage).

The nitrogen loads developed using this approach have been validated in a number of long and short-term field studies where integrated measurements of nitrogen discharge from watersheds could be directly measured. Weiskel and Howes (1991, 1992) conducted a detailed watershed/stream tube study that monitored septic systems, leaching fields and the transport of the nitrogen in groundwater to adjacent Buttermilk Bay. This monitoring resulted in estimated annual per capita nitrogen loads of 2.17 kg (as published) to 2.04 kg (if new attenuation information is included). 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 use based on average residential occupancy to measured average water uses. This is performed as a quality assurance check to increase certainty in the final results. This comparison has shown that the larger the watershed the better the match between average water use and occupancy. For example, in the cases of the combined Great Pond, Green Pond and Bournes Pond watershed in the Town of Falmouth and the Popponesset Bay/Eastern Waquoit Bay watershed, which covers large areas and have significant year-round populations, the septic nitrogen loading based upon the census data is within 5% of that from the water use approach. This comparison matches some of the variability seen in census data itself. Census blocks, which are generally smaller areas of any given town, have shown up to a 13% difference in average occupancy from town-wide occupancy rates. These analyses provide additional support for the use of the water use approach in the MEP study region.

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

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

In order to provide an independent validation of the average residential water use within the Sengekontacket Pond System watershed, MEP staff reviewed US Census population values for the Towns of Edgartown, Oak Bluffs, and West Tisbury. 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 Edgartown and West Tisbury is 2.39 people per occupied housing unit, while it is 2.34 in Oak Bluffs. Year-round occupancy of available housing units is 36%, 56%, and 42% for Edgartown, West Tisbury, and Oak Bluffs, respectively. Based on the average occupancy rate, the average water use by this calculation should be approximately 131 gpd per residence for Edgartown and West Tisbury and 128 gpd for Oak Bluffs. Given that such a high percentage of housing units are occupied on only a seasonal basis and the average measured water use includes this factor, the comparatively high average water use in the watershed (~215 gpd) suggests that a significant portion of the water use occurs during summer months and that seasonal dwellings use a disproportionably high amount of water.

Estimates of summer populations on Cape Cod and Martha's Vineyard, derived from a number of approaches (*e.g.*, traffic counts, garbage generation, WWTF flows), generally suggest average population increases from two to three times year-round residential populations measured by the US Census. Based upon the 2000 Census, seasonal properties make up, 42% (West Tisbury), 56% (Oak Bluffs), and 61% (Edgartown) of the residential units. Assuming that these seasonal residences are occupied at three times the year-round occupancy for three months, the estimated average town-wide water uses adjusted for seasonality would be 197, 193, and 197 gpd per residence, respectively. Given that the measured average water use for all water use accounts in the study area is within this range, this analysis suggests that the average water use is reasonably reflective of population estimates.

At the outset of the MEP, project staff decided to utilize the water use approach for determining residential wastewater generation by septic systems because of the inherent difficulty in accurately gauging actual occupancy in areas impacted by seasonal population fluctuations such as most of Cape Cod, Martha’s Vineyard, and Nantucket. The above analysis suggests that water use, on average, is a reasonable estimate of wastewater generation within the study area.

Water use information exists for 57% of the developed parcels in the Sengekontacket Pond System watershed. Parcels without water use accounts 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/or do not have a listed account in the water use databases. There are 634 developed parcels without water use accounts; these parcels are assumed to utilize private wells. Of these parcels, 85% are single family residences (land use code 101) and of these 345 (66%) of them are in the Ocean Heights subwatershed. For the purposes of determining the wastewater nitrogen load from these parcels, they were assigned average water use of properties with the same land use code within the watershed and, usually, within the same town.

Commercial and industrial properties were largely treated the same as residential properties, i.e. use of measured water use where available and assigned averages of measured water use for similarly classified land uses where measure water use is not available. There are 10 commercial properties in the Sengekontacket Pond watershed with another 7 that are classified as mixed use, but predominantly commercial. There are 8 commercial or mixed use and predominantly commercial parcels in the Trapp's Pond subwatershed that are connected to the Edgartown wastewater treatment facility (WWTF) sewer collection system.

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 residential lawns being the predominant source within this category. In order to add all of these sources to the nitrogen-loading model for the Sengekontacket Pond system, MVC staff under the guidance of MEP staff reviewed available information about residential lawn and athletic field fertilizing practices, crop fertilizer usage, and obtained information on fertilizer application rates at the three golf courses within the watershed.

Residential lawn fertilizer use has rarely been directly measured in watershed-based nitrogen loading investigations. Instead, lawn fertilizer nitrogen loads have been estimated based upon a number of assumptions: a) each household applies fertilizer, b) cumulative annual applications are 3 pounds of nitrogen per 1,000 sq. ft. of lawn, 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. The MEP fertilizer leaching rate of 20% recently received a detailed review prepared by Horsley Witten Group Inc. The task was to independently determine a nitrogen fertilizer leaching rate from turf grass specific to the permeable soils typical of the watersheds to southeastern Massachusetts estuaries, and then compare it to the MEP analysis. The analysis used both the results of previous studies and new data collected subsequent to the initiation of the MEP. The results indicated a leaching rate of 19% and the study concluded that "the MEP leaching rate estimate of 20% is reasonable (Horsley Witten Group, 2009).

In 1999, a land use survey on Martha's Vineyard reviewed lawn sizes, including portions of the Sengekontacket Pond watershed (MV Commission, 1999). This survey found that within the Sengekontacket Pond watershed the average lawn size was 3,300 square feet. MVC staff also determined individual lawn size on selected larger parcels and the area of selected ball fields based on review of aerial photographs; these site-specific areas were also included in the watershed loading model. Other factors in the model are those generally used in MEP nitrogen loading calculations.

Portions of the Farm Neck Golf Club, Vineyard Golf Club, and Edgartown Golf Club are located within the Sengekontacket Pond watershed. MVC staff were successful in obtaining site-specific fertilizer application rates for the Vineyard Golf Club, but unsuccessful in obtaining similar rates for the other two courses. The Vineyard Golf Club reported the following nitrogen fertilizer application rates for the various turf areas: greens, 2.0 pounds per 1,000 sq. ft; tees, 2.6 pounds per 1,000 sq. ft; fairways 2.7 pounds per 1,000 sq. ft., and roughs, 2.7 pounds per 1,000 sq. ft. Since the nitrogen application rates on the other courses are unavailable, MEP staff utilized the average nitrogen application rates from 14 golf courses previously contacted by MEP staff during the other estuary assessments were used to estimate the nitrogen load from the Farm Neck Golf Club and Edgartown Golf Club. These average nitrogen application rates are as follows: greens, 3.8 pounds per 1,000 sq. ft; tees, 3.5 pounds per 1,000 sq. ft; fairways 3.3 pounds per 1,000 sq. ft., and roughs, 2.5 pounds per 1,000 sq. ft. The area of the greens, tees, fairways, and roughs of the golf courses were determined from a review of aerial photographs and use of GIS techniques. The resulting loads are reduced by the amount reaching the groundwater, i.e., the leaching rate. The overall annual load from the three golf courses to Sengekontacket Pond is 1,038 kg.

One farm also exists in the watershed; MVC staff determined the areas of greenhouse and nursery. Nitrogen application rates for these areas are 68 and 55 kg per acre, respectively. Leaching rates were determined based on estimates of soil disturbance and are 0.1 and 0.33, respectively. Overall, farming occurs on 2.7 acres and adds 47 kg per year to the Sengekontacket Pond watershed.

Nitrogen Loading Input Factors: Landfill

The Oak Bluffs landfill is located off County Road and on a watershed boundary between Farm Pond, Sengekontacket Pond, Lagoon Pond, and Oak Bluffs Harbor. According to MVC staff, the landfill was capped in 1998. MVC staff determined the area within each watershed from a review of aerial photographs and use of GIS techniques and obtained groundwater monitoring data from wells around the landfill collected between 1990 and 2009.

This groundwater monitoring data included nitrate-nitrogen and limited ammonium-nitrogen data, but did not include total nitrogen measurements or a complete set of ammonium-nitrogen data. Based on a previous review of monitoring data from the groundwater plume associated with the Town of Brewster landfill (Cambareri and Eichner, 1993), MEP staff determined a relationship between ammonium-nitrogen and alkalinity concentrations ($NH4-N = 0.0352*ALK - 0.3565$; $r2 = 0.82$). This relationship was used to determine ammonium-nitrogen concentrations for Oak Bluffs landfill monitoring data where only nitrate-nitrogen and alkalinity data were available. Although nitrate-nitrogen and ammonium-nitrogen concentrations are not a complete measure of all nitrogen species, landfills do not tend to release significant portions of dissolved organic nitrogen (Pohland and Harper, 1985).

MEP staff reviewed the available and estimated inorganic nitrogen monitoring data collected since 2006 in order to better match the timeframe associated with the estuary water quality monitoring data collection. This review found that the average of the inorganic nitrogen concentration in the three monitoring wells downgradient of the landfill is 3.69 ppm, while the average concentration in the upgradient well is 0.2 ppm. Using the difference of 3.49 ppm, the Martha's Vineyard-specific recharge rate, and the area of the landfill within the Sengekontacket Pond watershed, MEP staff estimated that the annual nitrogen load from the Oak Bluffs landfill to Sengekontacket Pond is 26 kg.

Nitrogen Loading Input Factors: Other

One of the other key factors in the nitrogen loading calculations is recharge rates associated with impervious surfaces and natural areas. As discussed in Chapter III, Martha's Vineyard-specific recharge rates were developed and utilized based on comparison to the precipitation data in Edgartown and results of the USGS groundwater modeling effort on Cape Cod. Other 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). Factors used in the MEP nitrogen loading analysis for the Sengekontacket Pond watershed are summarized in Table IV-1.

Table IV-1. Primary Nitrogen Loading Factors used in the Sengekontacket Pond MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Oak Bluffs or Martha's Vineyard data.

Nitrogen Concentrations:	mg/l	Recharge Rates:	in/yr
Road Run-off	1.5	Impervious Surfaces	42.2
Roof Run-off	0.75	Natural and Lawn Areas	28.7
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:	
Natural Area Recharge	0.072	Existing developed residential parcels and buildout residential parcels:	Measured water use or watershed town-specific averages of:
Wastewater Coefficient	23.63		
Fertilizers:		Edgartown	209 gpd
Average Residential Lawn Size (sq ft)[1]:	3,300	Oak Bluffs	227 gpd
		West Tisbury	216 gpd
Residential Watershed Nitrogen Rate (lbs/1,000 sq ft)	1.08	Commercial and industrial buildout additions:	21 gpd /1,000 ft2 of building
Leaching Rate	0.2	Commercial and industrial building coverage of developed lots and buildout additions:	28%
Golf Course Fertilizers (Farm Neck and Edgartown Golf Clubs)[2]	lbs N/1,000 sq ft	Golf Course Fertilizer (Vineyard Golf Club)[3]	lbs N/1,000 sq ft
Greens	3.8	**GREENS**	2.0
Tees	3.5	Tees	**2.6**
Fairways	3.3	Fairways	2.7
Roughs	2.5	Roughs	2.7

[1] Data from 1999 Martha's Vineyard lawn survey.

[2] average nitrogen application rates based on information provided to MEP staff by course superintendents from 14 courses gathered during other MEP assessments

[3] reported by course superintendent to MVC staff

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 review of individual parcels straddling watershed boundaries included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Individualized information for parcels with atypical nitrogen loading (condominiums, golf courses, etc.) was also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the Sengekontacket Pond estuary. The assignment effort was undertaken to better define the sub-embayment loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

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

For management purposes, the aggregated embayment watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Sengekontacket Pond System, the major types of nitrogen loads are: wastewater (e.g., septic systems), the Oak Bluffs landfill, fertilizer (including residential lawns and golf courses), impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-3). In general, the annual watershed nitrogen 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. Natural nitrogen attenuation in the Sengekontacket Pond watershed only occurs to nitrogen that passes through Fresh Pond.

Freshwater Pond Nitrogen Loads

Freshwater ponds on Cape Cod, Martha's Vineyard, and Nantucket are generally kettle hole depressions of the land surface that intercept the surrounding groundwater table revealing what some call "windows on the aquifer." Groundwater typically flows into the pond along the upgradient shoreline, then lake water flows back into the groundwater system along the downgradient shoreline. Occasionally these ponds will also have a stream outlet or herring run that also acts as a discharge point. Since the nitrogen loads usually flow into a pond with the groundwater, the relatively more productive pond ecosystems incorporate some of the nitrogen, retain some nitrogen in the sediments, and change the nitrogen among its various oxidized and

Table IV-2. Sengekontacket Pond Nitrogen Loads. Present nitrogen loads are based on current conditions, including wastewater from onsite septic systems, fertilizer loads from golf courses and farms and loads from the Oak Bluffs landfill, in addition to atmospheric deposition and loading from natural surfaces (forests, grasslands, etc.). Buildout loads include septic, fertilizer, and impervious surface additions from developable properties. All values are kg N yr^{-1}.

		Sengekontacket Pond N Loads by Input (kg/yr):									**Present N Loads**				**Buildout N Loads**		
Name	**Watershed ID#**	**Wastewater**	**Landfill**	**Fertilizers**	**Farms**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**% of Pond Outflow**	**UnAtten N Load**	**Atten %**	**Atten N Load**		**UnAtten N Load**	**Atten %**	**Atten N Load**
System Total		**10255**	**26**	**1540**	**47**	**972**	**4110**	**851**	**4595**		**17802**		**17781**		**22396**		**22374**
Farm Neck	1	2079	26	811	0	315	0	206	560		3437	0%	3437		3997	0%	3997
State Beach	6	0	0	0	0	25	0	17	0		42	0%	42		42	0%	42
Ocean Heights	3	3994	0	342	0	239	0	266	2446		4840	0%	4840		7286	0%	7286
Majors Total		3440	0	157	47	284	486	285	503		4699		4678		5202		5180
Majors	2	3198	0	145	0	246	0	266	477		3855	0%	3855		4332	0%	4332
Fresh Pond	5	242	0	12	47	38	51	19	26	100%	409	5%	389		436	5%	414
Majors Estuary Surface							434				434	0%	434		434	0%	434
Trapp's Pond Total		743		230	0	110	241	76	1085		1400		1400		2485		2485
Trapp's Pond	4	743	0	230	0	110	0	76	1085		1159	0%	1159		2244	0%	2244
Trapp's Pond Estuary Surface							241				241	0%	241		241	0%	241
Sengekontacket Pond Estuary Surface		0	0	0	0	0	3383	0	0		3383	0%	3383		3383	0%	3383

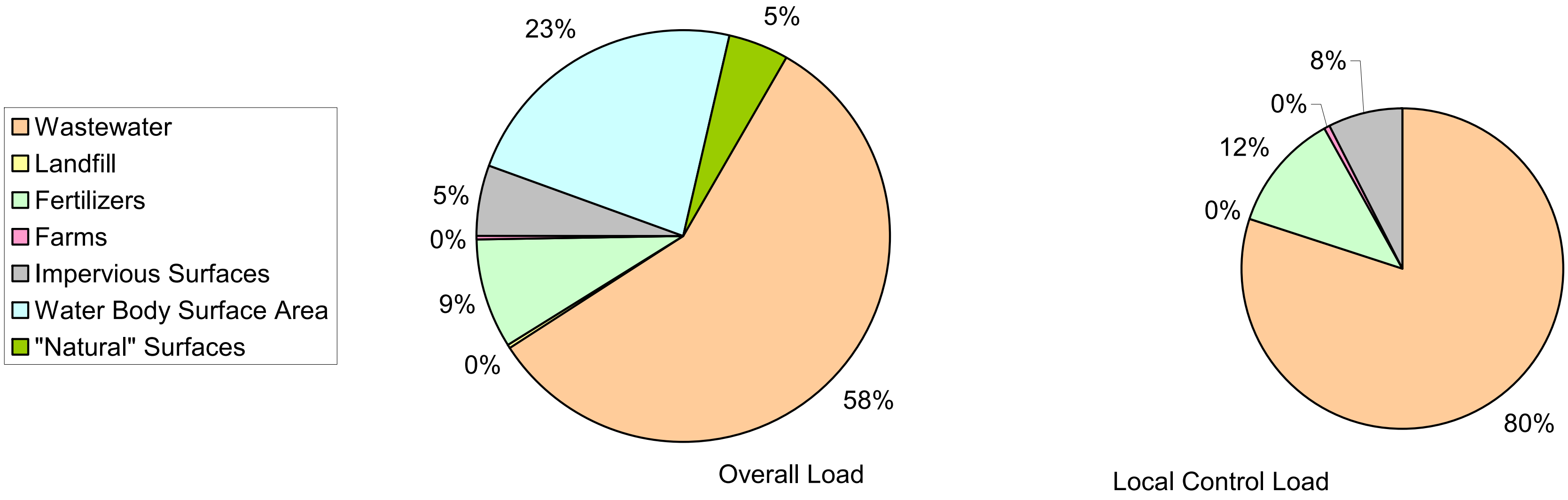

Figure IV-3. Land use-specific unattenuated nitrogen load (by percent) to the overall Sengekontacket Pond System watershed. “Overall Load” is the total nitrogen input within the watershed, including from natural surfaces, plus atmospheric deposition, while the “Local Control Load” represents only those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

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 (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 to Fresh Pond, the only freshwater pond in the Sengekontacket Pond watershed with a delineated watershed.

Nitrogen attenuation in freshwater ponds has generally been found to be at least 50% in MEP analyses, so a conservative attenuation rate of 50% is generally assigned to all nitrogen from freshwater pond watersheds in the watershed model unless more detailed pond monitoring or studies are available. Detailed studies of other southeastern Massachusetts freshwater systems including Ashumet Pond (AFCEE, 2000) and Agawam/Wankinco River Nitrogen Discharges (CDM, 2001) have supported a 50% attenuation factor as a reasonable, somewhat conservative rate. However, in some cases, if sufficient monitoring information is available, a pond-specific attenuation rate is incorporated into the watershed nitrogen loading modeling (*e.g.*, Three Bays MEP Report, 2005). In order to review whether a site-specific nitrogen attenuation rate should be used for a specific pond, the MEP Technical Team reviews the available data on each pond, including available nitrogen concentrations, impacts of sediment regeneration, temperature profiles, and bathymetric information.

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

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

Within the Sengekontacket Pond watershed, Fresh Pond is the only freshwater pond with a delineated watershed. Fresh Pond has a bathymetric map that is based on data gathered by MVC staff (William Wilcox, MVC, personal communication). Based on this bathymetric map, Fresh Pond has a maximum depth of approximately 4 m and a total volume of 81,425 cubic meters. Based on the Fresh Pond watershed, the residence time of water in the pond is 0.25 years.

Fresh Pond also has water quality data that was collected in: 1999 (once in June, September, and October), 2005 (twice a month between June and August and once in September), and 2008 (once in August). Water quality samples were analyzed by a number of laboratories, but only the samples analyzed at the SMAST Coastal System Program lab included total nitrogen analysis. These latter samples were collected in August and September of 2005 and August of 2008.

Using the water quality data, Fresh Pond has between 101 and 113 kg of nitrogen. With a residence time of 0.25 yrs, this means that 403 to 452 kg of nitrogen must enter the pond to sustain the measured mass of nitrogen in the pond. MEP staff reviewed the shallow and deep sample results and found no significant differences in the concentrations, so no distinct sediment load can be determined. Given that the estimated nitrogen load from the Fresh Pond watershed is 409 kg, the natural nitrogen attenuation in Fresh Pond is very low. Although this is not common, previous MEP-related assessments of freshwater ponds with short residence times have shown nitrogen attenuation rates lower than expected (e.g., Mill Pond in Howes, et al., 2006). For the purposes of this Sengekontacket Pond assessment, MEP staff assigned a nitrogen attenuation rate of 5% to Fresh Pond.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment (or scenario) of potential development within the study area watershed. For the Sengekontacket Pond modeling, MVC staff under the guidance of MEP staff reviewed individual properties for potential additional development. This review included assessment of minimum lot sizes based on current zoning, potential additional development on existing developed lots, and review of guesthouse provisions available under local regulations.

The buildout procedure used in this watershed and generally completed by MEP staff is to evaluate town zoning to determine minimum lot sizes in each of the zoning districts, including overlay districts (*e.g.*, water resource protection districts). Larger lots are subdivided by the minimum lot size to determine the total number of new lots. In addition, existing developed properties are reviewed for any additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence are assumed to have one additional residence at buildout. Most of the focus of new development is for properties classified as developable by the local assessor (state class land use codes 130 and 131 for residential properties). Properties classified by the town assessors as “undevelopable” (e.g., codes 132 and 392) were not assigned any development at buildout. Commercial and industrial developable properties were not subdivided; the area of each parcel and the factors in Table IV-1 were used to determine a wastewater flow for these properties. Based on the buildout assessment completed for this review, there are 554 potential additional residential dwellings and 139 potential additional guesthouse additions. There are also 1.6 acres and 5.2 acres of land classified as developable commercial land and developable industrial land, respectively. MVC staff reviewed the development potential of these two properties and did not assign the industrial property any additional development under the buildout scenario and assigned the commercial property no additional wastewater load. All parcels included in the buildout assessment of the Sengekontacket Pond watershed are shown in Figure IV-4.

Table IV-2 presents a sum of the additional nitrogen loads by subwatershed for the buildout scenario. This sum includes the wastewater, fertilizer, and impervious surface loads from additional residential dwellings added, as well as loads from projected guesthouse and commercial buildout additions. Overall, buildout additions within the entire Sengekontacket Pond System watershed will increase the unattenuated loading rate by 26%.

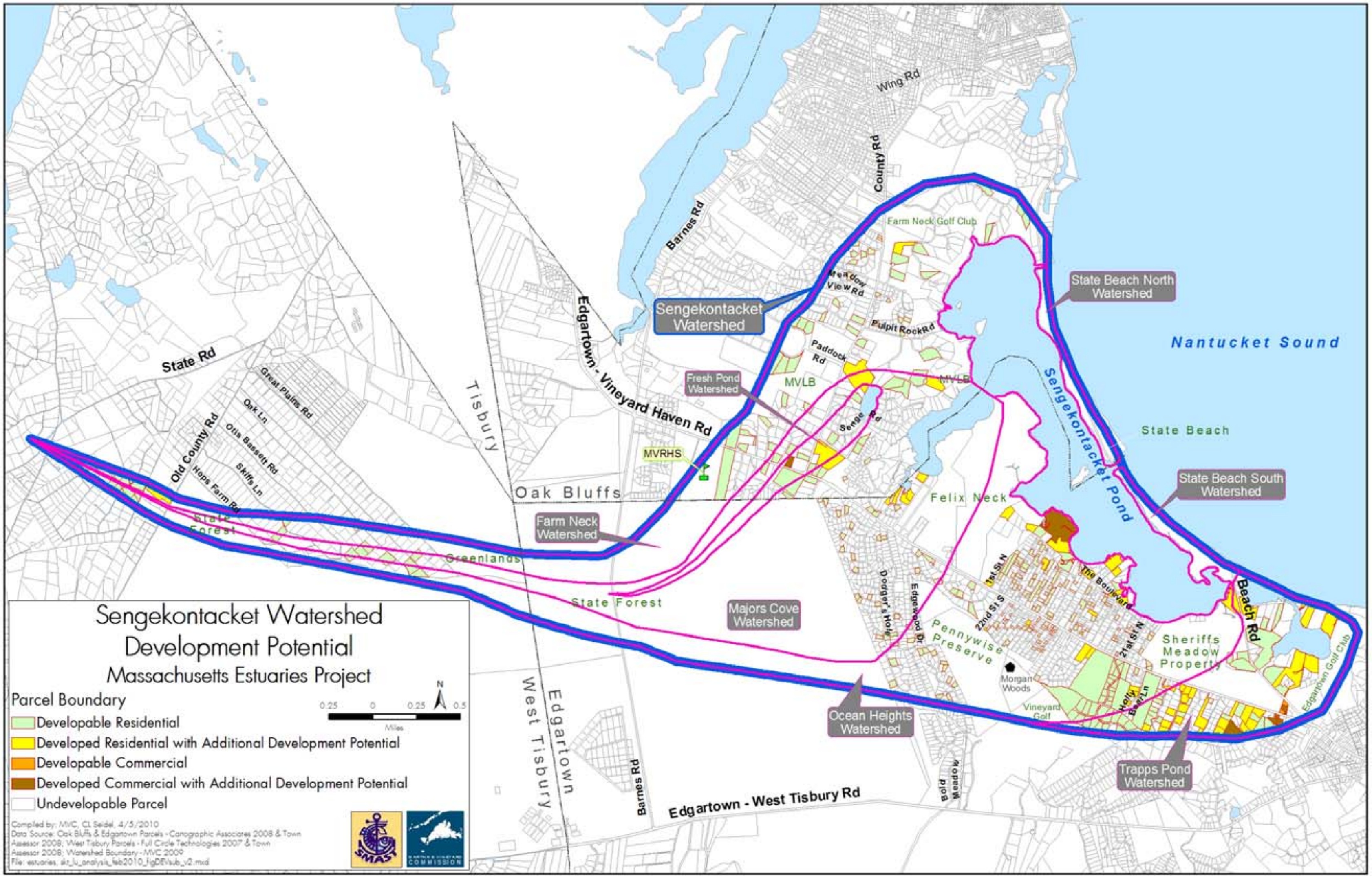

Figure IV-4. Developable Parcels in the Sengekontacket Pond watershed. Undeveloped parcels and developed parcels with additional development potential are highlighted. Nitrogen loads in the buildout scenario are based on additional development assigned to these parcels.

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 relative to the tidal flushing and nitrogen cycling within the embayment basins. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out or sewering analysis) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the watershed of the Sengekontacket Pond System were 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 is through groundwater in sandy outwash aquifers. The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. This is the case for the Sengekontacket Pond watershed. Unlike most watersheds in southeastern Massachusetts, nitrogen does not pass through a major surface water system on its path to the adjacent embayment. It is in these surface water systems that the needed conditions for nitrogen retention and denitrification exist. As there were no streams of measurable significance or great fresh ponds within the Sengekontacket Pond watershed, with the exception of Fresh Pond which had a very low residence time and low nitrogen attenuation rate (Section IV.1), almost all of the watershed nitrogen load reaching the water table was transported without attenuation in the groundwater system until discharge to the estuary.

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the benthic nutrient flux surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters throughout the Sengekontacket Pond 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 Sengekontacket Pond System predominantly in highly bio-available forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bio-available form nitrate. This nitrate and other bio-available forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like Atlantic Ocean or Vineyard/Nantucket Sound). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with their associated nitrogen "load" become incorporated into the surficial sediments of the bays.

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

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bio-available nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with deep depositional basins or salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh or Sesachacha Pond). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, for example in the margins of the main basin to Lewis Bay and Nantucket Harbor main basins or the lower basin of Lagoon Pond (behind the barrier beach). In contrast, most embayments show low rates of nitrogen release throughout much of basin area and in regions of high deposition typically support anoxic sediments with high release rates during summer months. The consequence of high deposition rates is that the basin sediments are unconsolidated, organic rich and sulfidic nature (MEP field observations).

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading to the Sengekontacket Pond System. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for Determining Sediment-Watercolumn Nitrogen Exchange

For the Sengekontacket Pond Embayment 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 (24 cores) were collected from 23 sites (Figure IV-5) in July-August 2004, focusing on the main lagoonal basin of Sengekontacket Pond and the tributary sub-embayments of Majors Cove and Trapps Pond Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Figure IV-5. Sengekontacket Pond System locations (red diamonds) of sediment sample collection for determination of nitrogen regeneration rates. Stations are distributed to capture variations in sediment regeneration relative to water quality gradients within this system. Numbers are for reference in Table IV-3.

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-5) per incubation are as follows:

Sengekontacket Pond System Benthic Nutrient Regeneration Cores

• SNG-1	1 core	(Farm Neck - North Main Basin)
• SNG-2	1 core	(Farm Neck - North Main Basin)
• SNG-3	1 core	(Farm Neck - North Main Basin)
• SNG-4	1 core	(Farm Neck - North Main Basin)
• SNG-5	1 core	(Farm Neck - North Main Basin)
• SNG-6	1 core	(Majors Cove)
• SNG-7	1 core	(Majors Cove)
• SNG-8	1 core	(Majors Cove)
• SNG-9	1 core	(Trapps Pond)
• SNG-10	1 core	(Trapps Pond)
• SNG-11	1 core	(Trapps Pond)
• SNG-12	1 core	(Majors Cove)
• SNG-13	1 core	(Mid - Main Basin)
• SNG-14	1 core	(Mid - Main Basin)
• SNG-15	1 core	(Mid - Main Basin)
• SNG-16	1 core	(Mid - Main Basin)
• SNG-17	1 core	(Ocean Heights - South Main Basin)
• SNG-18	1 core	(Ocean Heights - South Main Basin)
• SNG-19	1 core	(Ocean Heights - South Main Basin)
• SNG-20	1 core	(Ocean Heights - South Main Basin)
• SNG-21	1 core	(Ocean Heights - South Main Basin)
• SNG-22	1 core	(Ocean Heights - South Main Basin)
• SNG-23/24	2 cores	(Ocean Heights - South Main Basin)

Sampling was distributed throughout the primary embayment basin of this system: northern portion between the northern most tidal reach and Majors Cove (Farm Neck Basin), southern portion from Majors Cove to Trapps Pond (Ocean Heights Basin) and a Mid Basin, situated seaward of Majors Cove; plus the main tributary sub-embayments: Majors Cove and Trapps Pond. 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 (courtesy of the Town of Edgartown Shellfish Department and the Martha's Vineyard Rod and Gun Club), the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and ortho-phosphate (Murphy and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-20°C) for assay of nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON (D'Elia *et al.* 1977). Rates were determined from linear regression of analyte concentrations through time.

Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA [*508-910-6325*]. 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-6).

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

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

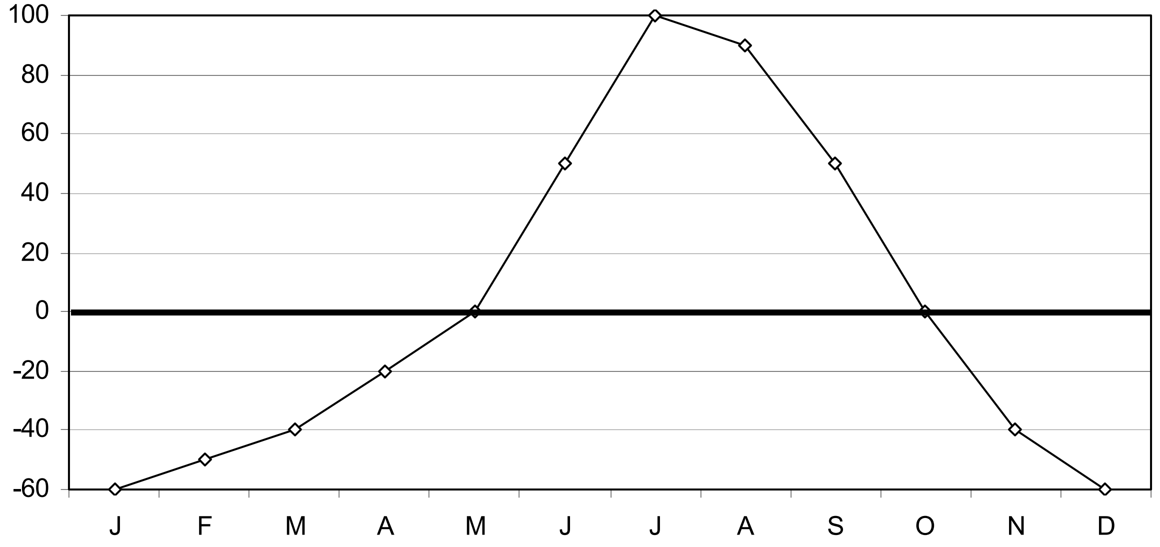

Figure IV-6. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Sediment sampling was conducted throughout the Sengekontacket Pond main basin and the major tributary sub-embayment basins of Majors Cove and Trapps Pond, 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 and spatial differences among the various basins. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content, as well as sediment type and an analysis of each site's tidal flow velocities. As expected flow velocities are generally low throughout Sengekontacket Pond except in the immediate vicinity of the two inlets. 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 are 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 shallow enclosed basins like Trapps Pond and 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.

Rates of net nitrogen release or uptake from the sediments within the Sengekontacket Pond Embayment System were comparable to other embayments of similar depth, sediment characteristics and nitrogen loading rates in southeastern Massachusetts. There was a clear pattern of sediment N flux, with the shallow main basin of Sengekontacket Pond generally composed of oxidized sediments (primarily in the northern and mid basins) and showing net uptake, -0.9 to -10.1 mg N m^{-2} d^{-1} or small net loss 4.7 mg N m^{-2} d^{-1}. In contrast, the sediments of the tributary sub-embayments of Majors Cove and Trapps Pond supported low-moderate levels of net nitrogen release, 13.8 mg N m^{-2} d^{-1} and 17.1 mg N m^{-2} d^{-1}, respectively. These latter basins are depositional with soft organic rich muddy sediments with a thin oxidized surface layer. Both the observed rates and their spatial distribution are similar to other estuarine basins in the region. Nearby Lagoon Pond was found to have net nitrogen uptake in the lagoon formed behind the barrier beach (-2.3 mg N m^{-2} d^{-1}) and net release in the adjacent basins within the eastern and western arms of the estuary of 8.4 and 31.8 mg N m^{-2} d^{-1}. Similarly, the shallow sandy oxidized sediments within the main basins of the Nantucket Harbor Embayment System also show net nitrogen uptake in summer of -7.9 to-38.8 mg N m^{-2} d^{-1}, while the main basin of Lewis Bay showed net release (6.9 mg N m^{-2} d^{-1}) and the shallower sediments showed net uptake (-11.6 and -32.0 mg N m^{-2} d^{-1}). The magnitude of the rates in other systems also clearly encompasses the rate observed for Majors Cove (13.8 mg N m^{-2} d^{-1}) where the sediments are nearly in balance with the watercolumn. Trapps Pond (17.1 mg N m^{-2} d^{-1}) is a tidally restricted basin with rates similar to the tidally restricted upper basins of the Madaket Harbor-Long Pond Embayment System (6 - 14 mg N m^{-2} d^{-1}).

Net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the Sengekontacket Pond Embayment System (Chapter VI) are presented in Table IV-3. There was a clear spatial pattern of sediment nitrogen flux, with net uptake of nitrogen in main basin behind the barrier beach and net release in the shallow depositional basins of Majors Cove and Trapps Pond. The sediments within the Sengekontacket System showed nitrogen fluxes comparable to many tidal embayments within the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to this system and its rates of tidal flushing.

Table IV-3. Rates of net nitrogen return from sediments to the overlying waters of the component basins of the Sengekontacket Pond 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})**			**Station ID ***
	Mean	**S.E.**	**# sites**	
Sengekontacket Pond Estuarine System				
Main Basin - Farm Neck	**-0.9**	**4.6**	**5**	SNG: 1-5
Main Basin - Mid	**4.7**	**7.0**	**4**	SNG: 13-16
Main Basin - Ocean Heights	**-10.1**	**8.1**	**8**	SNG: 17-24
Majors Cove	**13.8**	**20.9**	**4**	SNG: 6,7,8,12
Trapps Pond	**17.1**	**15.6**	**3**	SNG: 9,10,11

* Station numbers refer to Figure IV-5.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes field data collection effort and the development of hydrodynamic models for the Sengekontacket Pond estuary system (Figure V-1). 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 tool for later determining nitrogen loading "thresholds". Tidal flushing information is utilized as the basis for a quantitative evaluation of water quality. Nutrient loading data combined with measured environmental parameters within the various sub-embayments 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, as well as determining the likely positive impacts of various alternatives for improving overall estuarine health, enabling the bordering residence to understand how pollutant loadings into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

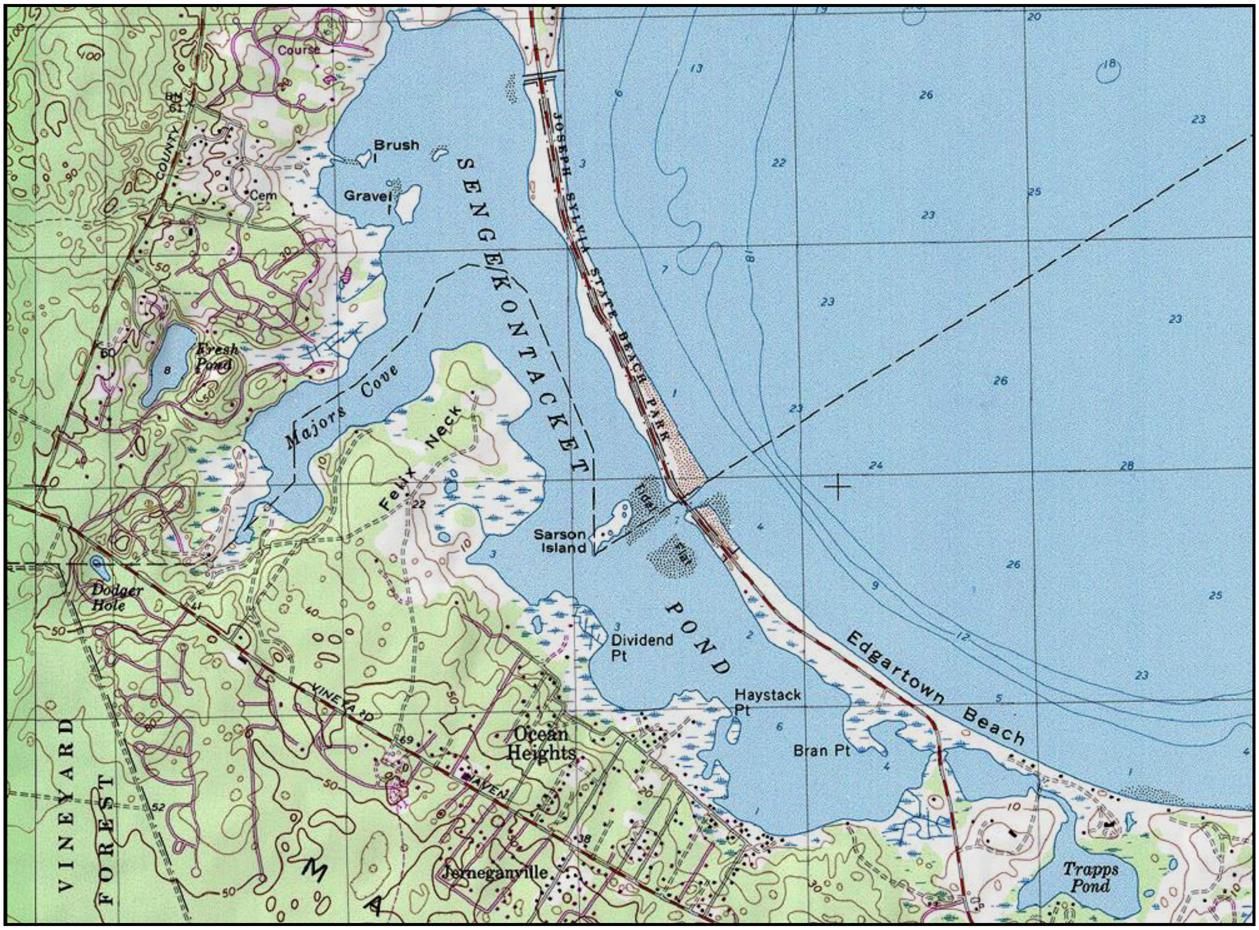

Figure V-1. Map of the Sengekontacket Pond estuary system (from United States Geological Survey topographic maps).

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.

Estuarine water quality is dependent upon nutrient and pollutant loading and the processes that help flush nutrients and pollutants from the estuary (e.g., tides and biological processes). Relatively low nutrient and pollutant loading and efficient tidal flushing are indicators of high water quality. The ability of an estuary to flush nutrients and pollutants is proportional to the volume of water exchanged with a high quality water body (i.e. Nantucket Sound). Several embayment-specific parameters influence tidal flushing and the associated residence time of water within an estuary. For the Sengekontacket Pond system, the most important parameters are the tide range along with the shape, length and depth of the estuary.

Shallow coastal embayments are the initial recipients of freshwater flows (i.e., groundwater and surface water) 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.

The Sengekontacket Pond system (Figure V-1) is a tidally dominated embayment with two inlets opening into Nantucket Sound. The inlets are maintained across the barrier beach at its eastern extent of the estuary system. The northern opening is located in the town of Oak Bluffs and is about 36 feet wide at it narrowest point. The southern opening is located at the town line between Edgartown and Oak Bluffs and is 229 feet wide at its narrowest point. Sengekontacket Pond has two main sub-embayments: Majors Cove, and Trapps Pond. Majors Cove is located on the northwest side of Sengekontacket Pond running along the northern extent of Felix Neck. Majors Cove is marked by a relatively deep channel down the center of the basin (varies between -5 and -7 feet) with steeply rising side slopes that provides a shallow perimeter around the basin. Trapps Pond is located at the southern extent of Sengekontacket Pond, and is comprised of two basins that extend southward. The northern basin is connected to Sengekontacket Pond through a culvert under Edgartown Oak Bluffs Road. The two basins are also separated in the middle by culvert structure under Cow Bay Road. The structures allow tidal exchange to occur between Sengekontacket and Trapps Pond.

Since the water elevation difference between Nantucket Sound and the inland reaches of the Sengekontacket Pond estuarine system is the primary driving force for tidal exchange, the local tide range in Nantucket Sound limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) along the length of Sengekontacket Pond is negligible, except for Trapps Pond which has a significant amount of tidal attenuation. The lack of tidal attenuation through the rest of the system indicates that the system is flushed efficiently. Any issues with water quality, therefore, would likely be due other factors including nutrient loading conditions from the system’s watersheds, and the tide range in Nantucket Sound. The tidal attenuation between Sengekontacket Pond and Trapps Pond indicates that issues with water quality would likely be due to inadequate flushing of the nutrients within the pond.

Circulation in Sengekontacket Pond estuarine system was simulated using the RMA-2 numerical hydrodynamic model. To calibrate the model, field measurements of water elevations and bathymetry were required. Tide data were acquired within Nantucket Sound at two gauge stations installed offshore of Sengekontacket Pond directly in front of both inlets. Six additional stations were located within Sengekontacket Pond (Figure V-2). All temperature-depth recorders (TDRs or tide gauges) were installed for a 34-day period to measure tidal variations through one spring-neap tidal cycle. In this manner, attenuation of the tidal signal as it propagates through the various sub-embayments was evaluated accurately.

V.2 FIELD DATA COLLECTION AND ANALYSIS

Accurate modeling of system hydrodynamics is dependent upon measured conditions within the estuary for two important reasons:

To define accurately the system geometry and boundary conditions for the numerical model
To provide ‘real’ observations of hydrodynamic behavior to calibrate and verify the model results

System geometry is defined by the shoreline of the system, including all coves, creeks, and marshes, as well as accompanying depth (or bathymetric) information. The three-dimensional surface of the estuary is mapped as accurately as possible, since the resulting hydrodynamic behavior is strongly dependent upon features such as channel widths and depths, sills, marsh elevations, and inter-tidal flats. Hence, this study included an effort to collect bathymetric information in the field.

Boundary conditions for the numerical model consist of variations of water surface elevations measured in Nantucket Sound. These variations result principally from tides, and provide the dominant hydraulic forcing for the system, and are the principal forcing function applied to the model. Additional pressure sensors were installed at selected interior locations to measure variations of water surface elevation along the length of the system (gauging locations are shown in Figure V-2). These measurements were used to calibrate and verify the model results, and to assure that the dynamic of the physical system were properly simulated.

To complete the field data collection effort for this study, and to provide model verification data, a survey of velocities was completed at both inlets to Sengekontacket Pond. The survey was performed to determine flow rates at both inlets at discreet times during the course of a full tide cycle.

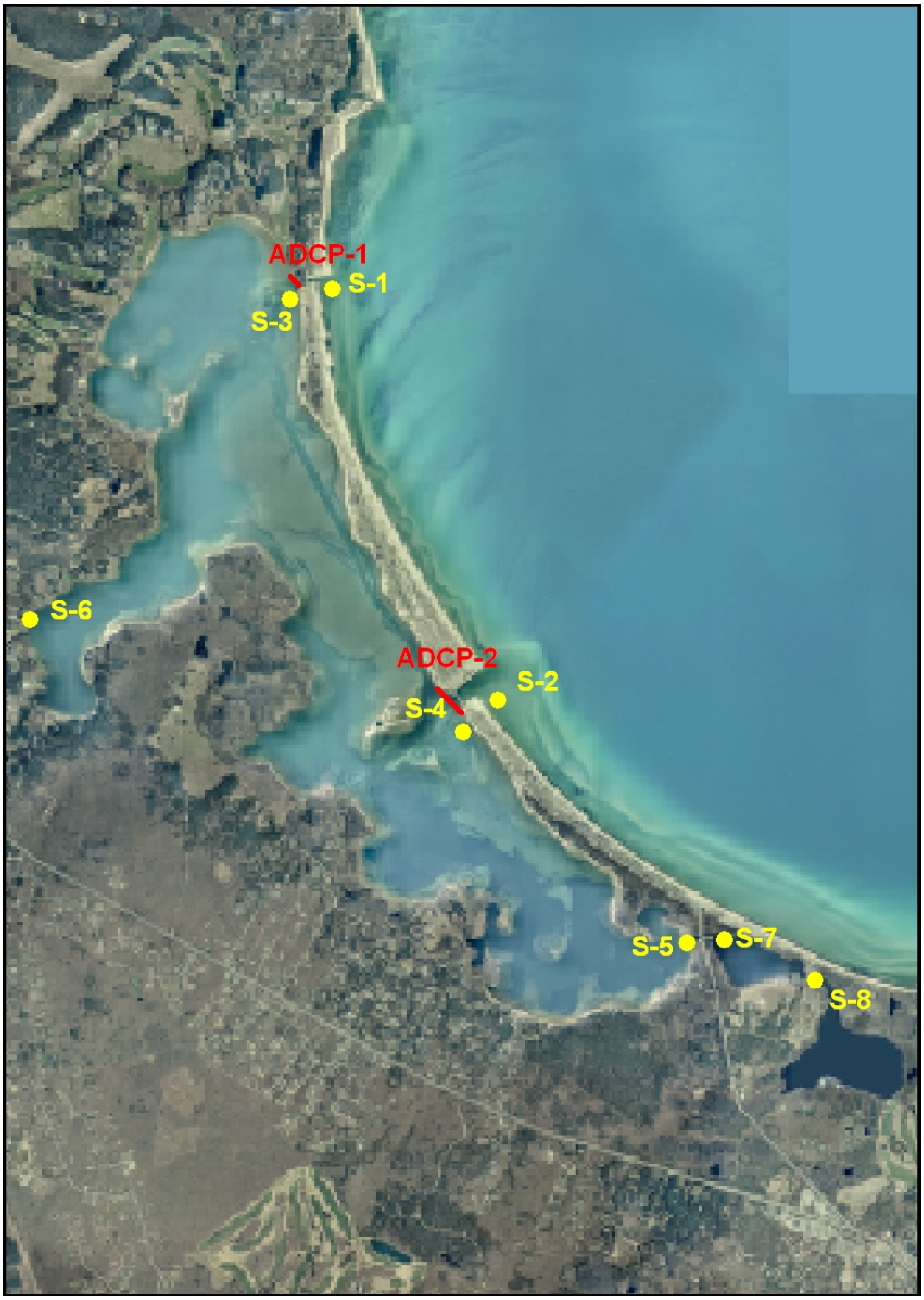

Figure V-2. Map of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. Eight (8) gauges were deployed for the 34-day period between Oct 18, and Nov 21, 2005. Each yellow dot represents the approximate locations of the tide gauges: (S-1) represents the north gauge in Nantucket Sound (Offshore), (S-2) south gauge in Nantucket Sound, (S-3) the gauge inside the north inlet, (S-4) gauge inside the south inlet, (S-5) south gauge in Sengekontacket Pond, (S-6) Majors Cove gauge, (S-7) northern Trapps Pond gauge, (S-8) southern Trapps Pond gauge.

V.2.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Sengekontacket Pond system was assembled from two recent hydrographic surveys performed specifically for this study. Bathymetry for Nantucket Sound was available from National Oceanic and Atmospheric Administration (NOAA). NOAA conducted a multi-beam survey offshore of Edgartown in 2004 which include the region immediately offshore of Sengekontacket Pond.

The first of two hydrographic surveys were conducted over several days between October 18 and October 20, 2005. The survey collected bathymetry in Sengekontacket Pond and Majors Cove. The second hydrographic survey was conducted on October 21, 2005, was designed to collect shallow water bathymetry in Trapps Pond. Survey transects in both cases were densest in the vicinity of the inlets and channel constrictions, were the greatest variability in bottom bathymetry was expected. Bathymetry in the inlets is important from the standpoint that they have the most influence on tidal circulation in and out of the estuary. The first survey was conducted from a shoal draft outboard boat with a precision fathometer installed (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide position measurements accurate to approximately 1-3 feet. Digital data output from both the echo sounder (fathometer) and GPS were logged to a laptop computer, which integrated the data to produce a single data set consisting of water depth as a function of geographic position (latitude/longitude). The second survey was conducted from a canoe with an installed precision fathometer (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide position measurements accurate to approximately 1-3 feet. Digital data output from both the echo sounder (fathometer) and GPS were logged into the GPS Data Logger. A digital output from the Data Logger produced a single data set consisting of water depth as a function of geographic position (latitude/longitude).

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to United States Coast and Geodetic Survey (USC&GS) Mean Low Water (MLW) vertical datum. Once rectified, the finished processed data were archived as ‘xyz’ files containing x-y horizontal position (in Massachusetts State Plan 1983 coordinates) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The final processed bathymetric data from the survey are presented in Figure V-3.

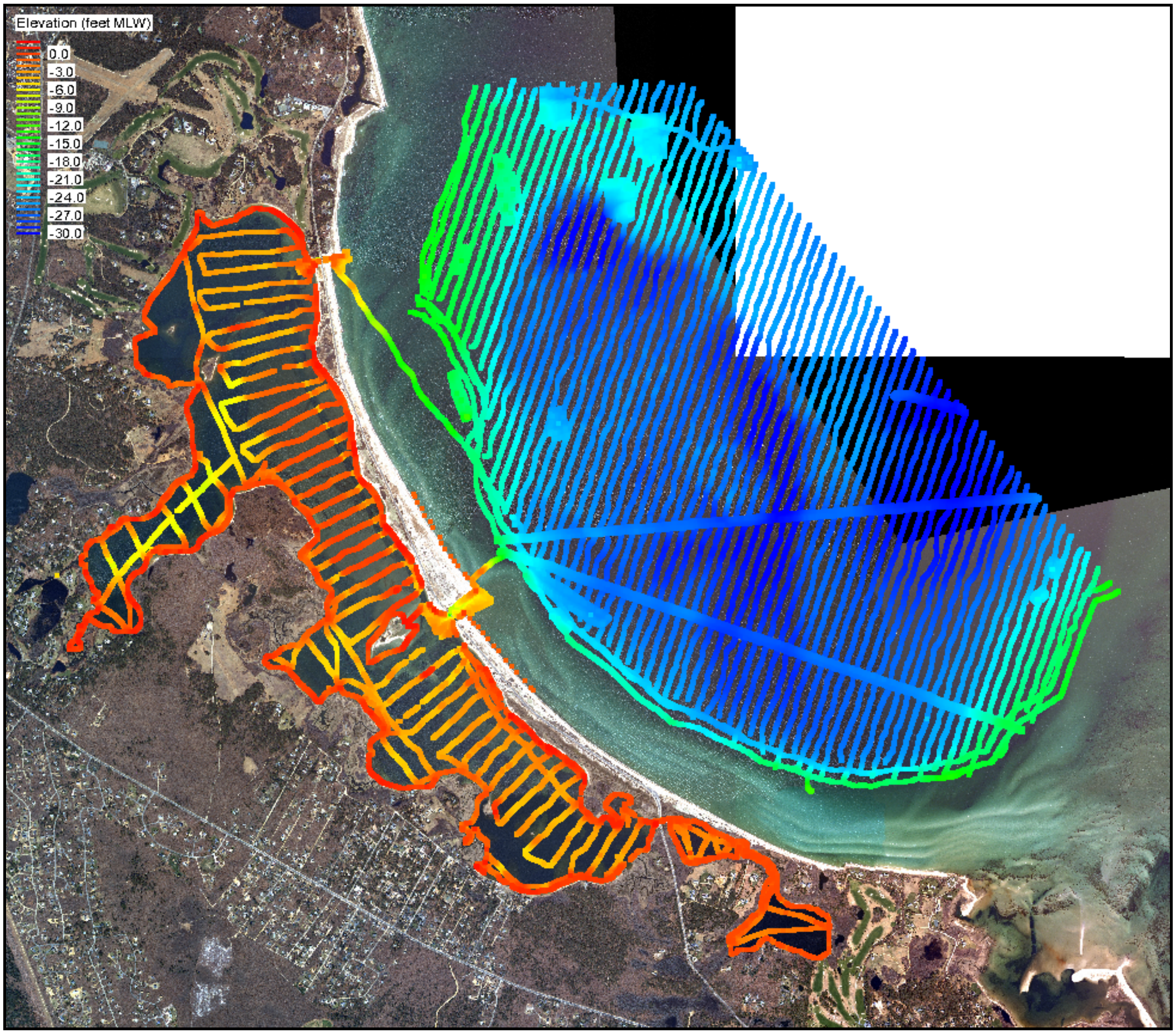

Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

V.2.2 Tide Data Collection and Analysis

Variations in water surface elevation were measured at a station in at six locations in the Sengekontacket Pond, and at two stations in Nantucket Sound. The first location in Nantucket Sound is located just offshore of the northern breach in Nantucket Sound (S-1) and the second location of an off shore tide gauge is located outside of the southern breach in Nantucket Sound (S-2). Stations within the Sengekontacket Pond estuary system were located inside the north inlet on the south bank (S-3), inside the south inlet on the south bank (S-4), south gauge in Sengekontacket Pond just north of the culvert under Edgartown Oak Bluffs Road (S-5), Majors Cove gauge was located just east of the Sengekontacket Road boat ramp (S-6), northern Trapps Pond gauge was located just south of the Edgartown Oak Bluffs Road culvert (S-7), and the southern Trapps Pond gauge was located just south of the Cows Bay Road culvert (S-8). TDRs were deployed at each gauging station from October 18 through November 21, 2005. The duration of the TDR deployment allowed time to conduct the ADCP and bathymetric surveys, as well as sufficient data to perform a thorough analysis of the tides in the system.

The tide records from Sengekontacket Pond were corrected for atmospheric pressure variations and then rectified to the NSC&GS MLW vertical datum. Atmospheric pressure data, available in one-hour intervals from the NDBC Nantucket Sound C-MAN platform, were used to pressure correct the raw tide data. Final processed tide data from stations used for this study are presented in Figure V-4, for the complete 34-day period of the TDR deployment.

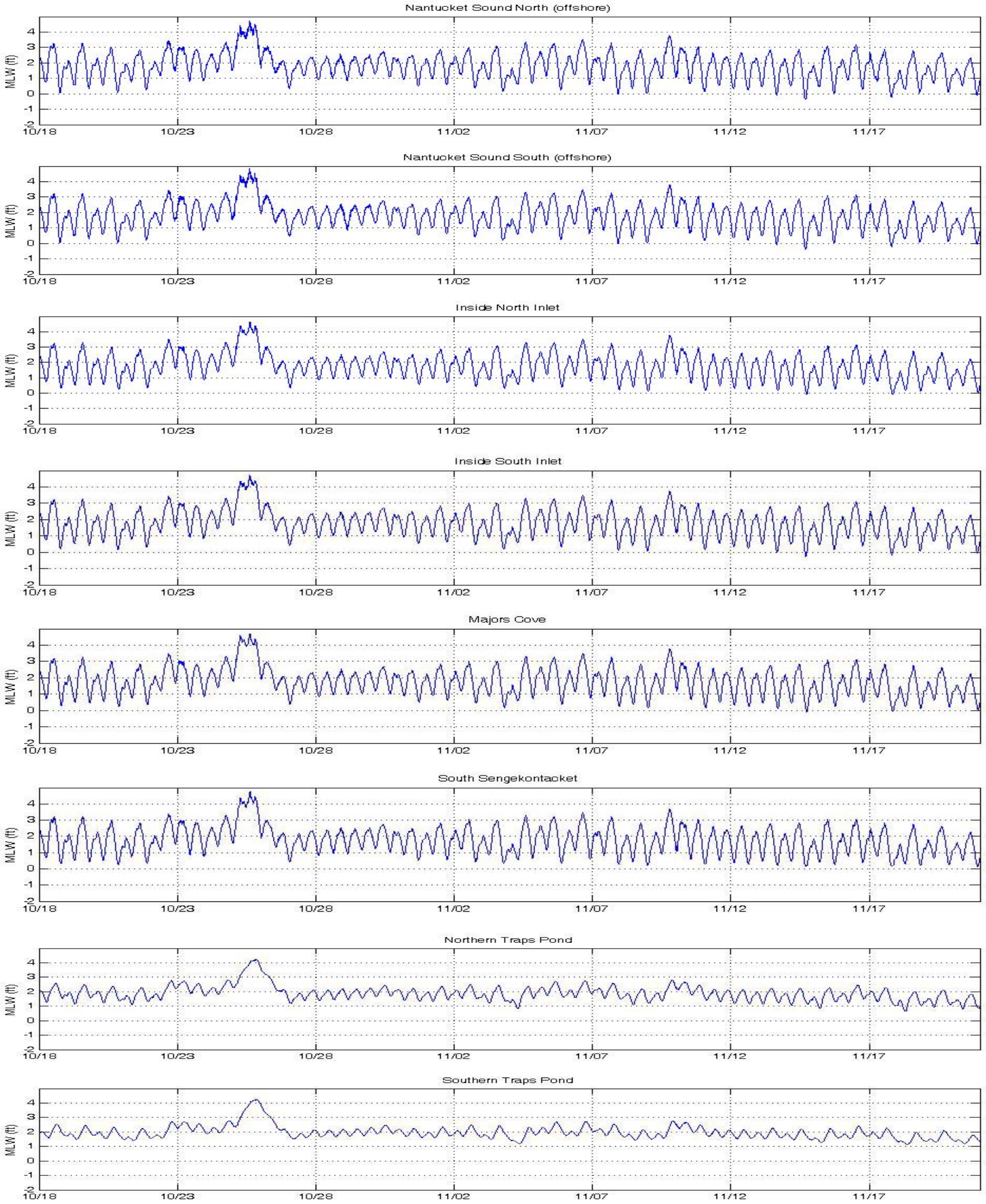

Figure V-4. Water elevation variations as measured at the eight locations of the Sengekontacket Pond system, from October 18 through November 21, 2005.

Tide records longer than 29.5 days are necessary for a complete evaluation of tidal dynamics within the estuarine system. Although a one-month record likely does not include extreme high or low tides, it does provide an accurate basis for typical tidal conditions governed by both lunar and solar motion. For numerical modeling of hydrodynamics, the typical tide conditions associated with a one-month record are appropriate for driving tidal flows within the estuarine system.

The loss of amplitude together with increasing phase delay with increasing distance from the inlet is described as tidal attenuation. Tidal attenuation can be a useful indicator of flushing efficiency in an estuary. Attenuation of the tidal signal is caused by the geomorphology of the near-shore region, areas with channel restrictions (e.g. bridge abutments, culverts, shoals, etc.), and also the depth of an estuary are the primary factors which influence tidal damping in estuaries. A visual comparison of the eight stations throughout the Sengekontacket Pond estuary system is shown in Figure V-5. The figure demonstrates clearly the reduction in the tidal efficiency as the tide propagates into and through Trapps Pond.

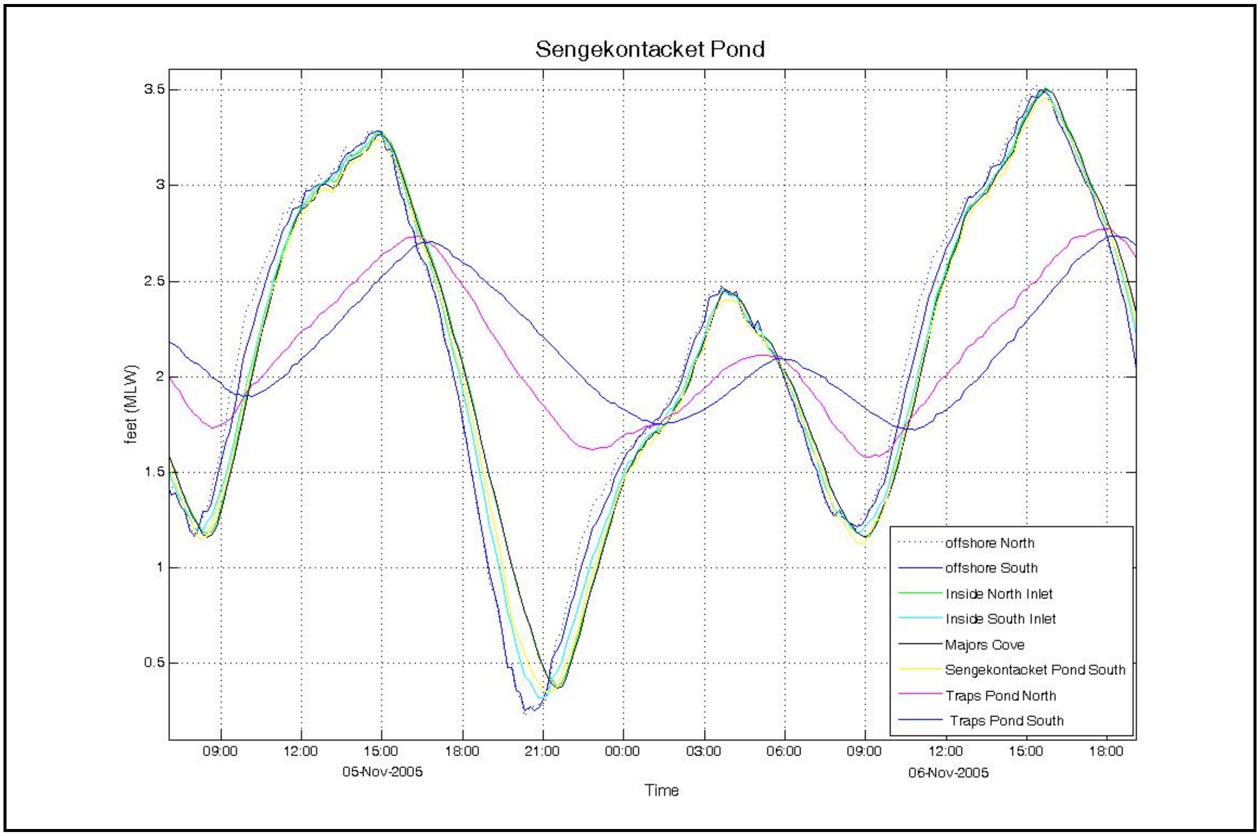

Figure V-5 Plot showing two tide cycles tides at eight stations in the Sengekontacket Pond system plotted together. Demonstrated in this plot is the amplitude reduction in Trapps Pond caused by the propagation of the tide through the culvert under Edgartown Oak Bluffs Road.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 34-day records. These datums are presented in Table V-1. The Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW. The tides in Nantucket Sound are semi-diurnal, meaning that there are typically two tide cycles in a day. There is usually a small variation in the level of the two daily tides. This variation can be seen in the differences between the MHHW and MHW, as well as the MLLW and MLW levels

For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data was available; however, these datums still provide a useful comparison of tidal dynamics within the system. From the computed datums, it further apparent that there is little tide damping throughout the system (with the noted exception of Trapps Pond). Again, the absence of tide damping exhibited in Sengekontacket Pond indicates that the system flushes efficiently.

A more thorough harmonic analysis was also performed on the time series data from each gauging station in an effort to separate the various component signals which make up the observed tide. The analysis allows an understanding of the relative contribution that diverse physical processes (i.e. tides, winds, etc.) have on water level variations within the estuary. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 tidal constituents, with periods between 4 hours and 2 weeks, result from this procedure. The observed tide is therefore the sum of an astronomical tide component and a residual atmospheric component. The astronomical tide in turn 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-6.

Table V-1. Tide datums computed from records collected in the Sengekontacket Pond estuarine system October 18 to November 21, 2005. Datum elevations are given relative to USC&GS MLW.

Tide Datum	Nantucket Sound (S-1)	Nantucket Sound (S-2)	North Inlet (S-3)	Majors Cove (S-6)	South Inlet (S-4)	Sengekontacket Pond (S-5)	Trapps Pond (S-7)	Trapps Pond (S-8)
Maximum Tide	4.71	4.84	4.63	4.68	4.73	4.75	4.23	4.25
MHHW	3.03	3.03	2.99	2.99	2.99	2.98	2.49	2.48
MHW	2.70	2.69	2.65	2.65	2.66	2.65	2.26	2.26
MTL	1.69	1.69	1.69	1.69	1.69	1.69	1.86	1.97
MLW	0.68	0.69	0.73	0.73	0.72	0.73	1.46	1.69
MLLW	0.38	0.40	0.49	0.48	0.44	0.50	1.29	1.59
Minimum Tide	-0.38	-0.38	-0.11	-0.09	-0.29	0.15	0.62	1.13

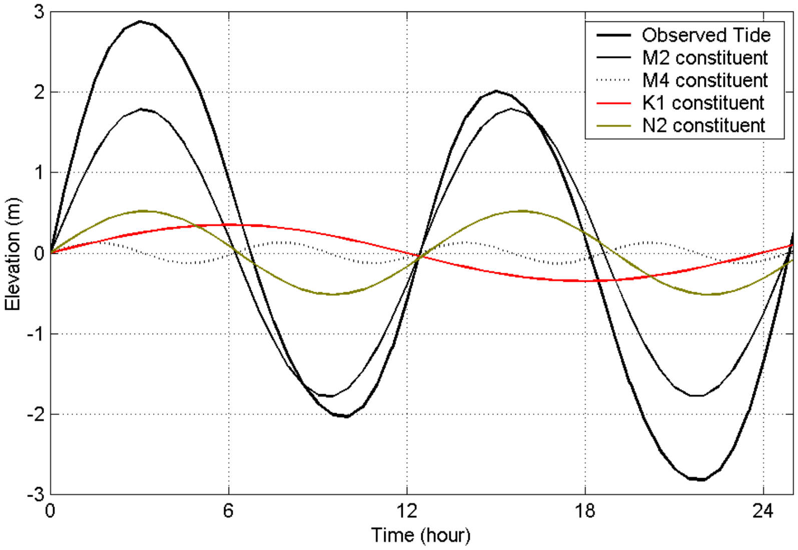

Figure V-6. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-2 presents the amplitudes of eight significant tidal constituents. The M_2, or the familiar twice-a-day lunar semi-diurnal, tide is the strongest contributor to the signal with an amplitude varying by only 0.03 ft from Nantucket Sound throughout all of Sengekontacket Pond with a range of 0.80-0.83 feet. In contrast a significant reduction of the M_2 values in Trapps Pond again shows the reduction of amplitude caused in large part by the culvert under Edgartown Oak Bluffs Road between Sengekontacket Pond and Trapps Pond. The range of the M_2 tide is twice the amplitude, or about 1.60-1.64 feet in Sengekontacket Pond and 0.46-0.66 feet in Trapps Pond. In Sengekontacket Pond the diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar), possess amplitudes of approximately 0.30-0.29 feet and 0.24 feet respectively and account for the semi-diurnal variance one high/low tide to the next, seen in Figure V-5. The N_2 tide, a lunar constituent with a semi-diurnal period, is the next largest tidal constituent and is a little more than 4 times smaller than the main semi-diurnal constituent (M_2) with an amplitude of 0.38 feet. The M_4 and M_6 tides are higher frequency harmonic of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water. The M_4 is already large at the system inlet, with an amplitude of 0.2 feet. The M_6 has a very small amplitude throughout the system (about 0.07 feet at the inlet and 0.01-0.02 feet back in Trapps Pond).

Table V-2. Tidal Constituents for the Sengekontacket Pond System. Data collected October 18 to November 21, 2005.

AMPLITUDE (feet)							
	M2	M4	M6	S2	N2	K1	O1
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82
Nantucket Sound - North (S-1)	0.82	0.21	0.07	0.06	0.19	0.30	0.24
Nantucket Sound - South (S-2)	0.83	0.18	0.05	0.07	0.19	0.29	0.24
Inside North Inlet (S-3)	0.80	0.15	0.08	0.07	0.17	0.29	0.24
Majors Cove (S-6)	0.80	0.15	0.08	0.06	0.17	0.29	0.24
Inside South Inlet (S-4)	0.82	0.17	0.05	0.07	0.18	0.29	0.24
Sengekontacket Pond - South (S-5)	0.81	0.17	0.06	0.06	0.17	0.29	0.24
Trapps Pond - North (S-7)	0.33	0.07	0.02	0.03	0.05	0.15	0.13
Trapps Pond - South (S-8)	0.23	0.01	0.01	0.02	0.04	0.14	0.12

Table V-3 presents the phase delay (in other words, the travel time required for the tidal wave to propagate throughout the system) of the M_2 tide at all tide gauge locations inside the system. The greatest delay occurs between the Nantucket Sound gauging station and Trapps Pond gauging stations. The largest changes in phase delay occur between the Trapps Pond gauging stations and Sengekontacket Pond. This indicates the degree of hydraulic inefficiency being caused by the culverts into and in Trapps Pond. The negative delay between the south and north inlets shows the phasing of the tide as it moves along the coastline, the tide signal at the north inlet is ahead of the south inlet by approximately 8 minutes.

Table V-3. M2 Tidal Attenuation within Sengekontacket Pond Estuary System, October 18 to November 21, 2005 (Delay in minutes relative to Nantucket Sound gauge S-2).

Location	Delay (minutes)
Nantucket Sound - North (S-1)	-7.62
Inside North Inlet (S-3)	25.17
Majors Cove (S-6)	25.77
Inside South Inlet (S-4)	12.74
Sengekontacket Pond - South (S-5)	17.79
Trapps Pond - North (S-7)	78.69
Trapps Pond - South (S-8)	171.58

The tide data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. Non-tidal 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 system is presented in Table V-4 compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 23 constituents determined by the harmonic analysis). Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes are relative to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from Nantucket Sound, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual. The influence of storm can be clearly seen on October 25, 2005 in the plot of the residual tide, the storm produced winds out of the northeast which resulted in a surge of approximately 2 feet along the coast. The record was shortened to remove the storm from the analysis to provide a more accurate comparison of energy distribution during normal conditions.

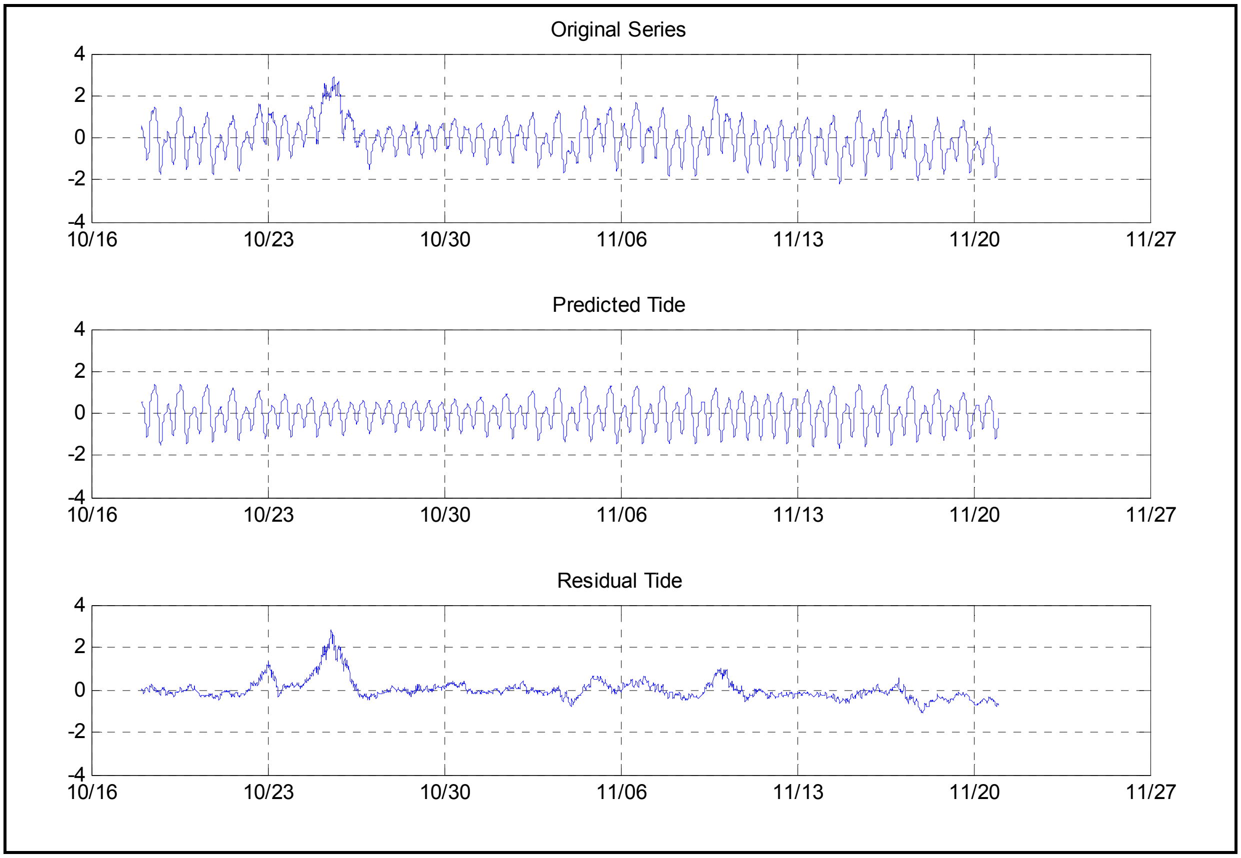

Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured in Nantucket Sound at gauge location S-1.

Table V-4 shows that the percentage contribution of tidal energy was the predominant driving force of the observed tidal signal, which indicates that local effects due to winds and other non-tidal processes are minimal throughout the system. The analysis also shows that tides are responsible for approximately 80% of the water level changes in the Sengekontacket Pond system. The remaining 20% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of Nantucket Sound and the Sengekontacket Pond system. The total energy content of the tide signal should carry over from one embayment to the next unless tidal flow is inhibited. The tidal energy in Trapps Pond illustrates the inhibited flow from the gauging stations in Sengekontacket Pond. In this case the entire tidal signal is significantly delayed and reduced by the restrictive flow through the culverts into and out of the pond. This can also be seen in the increase percent of non-tidal factors influencing the tidal signal in Trapps Pond.

Table V-4. Percentages of Tidal versus Non-Tidal Energy, Sengekontacket Pond.

Location	Total Variance (ft^2)	Total (%)	Tidal (%)	Non-tidal (%)
Nantucket Sound - North (S-1)	0.59	100	81.4	18.6
Nantucket Sound - South (S-2)	0.59	100	80.8	19.2
Inside North Inlet (S-3)	0.56	100	79.1	20.9
Majors Cove (S-6)	0.55	100	79.6	20.4
Inside South Inlet (S-4)	0.58	100	81.2	18.8
Sengekontacket Pond - South (S-5)	0.55	100	81.8	18.2
Trapps Pond - North (S-7)	0.19	100	46.3	53.7
Trapps Pond - South (S-8)	0.14	100	35.7	64.3

The results from Table V-4 indicate that hydrodynamic circulation throughout Sengekontacket Pond is dependent primarily upon tidal processes. When wind and other non-tidal effects are a less significant portion of the total variance, the residual signal should not be ignored. Therefore, for the hydrodynamic modeling effort described below, the actual tide signal from Nantucket Sound was used to force the model so that the effects of non-tidal energy are included in the modeling analysis.

V.2.3 ADCP Data Analysis

The measurements were collected using an Acoustic Doppler Current Profiler (ADCP) mounted aboard a small survey vessel. The boat repeatedly navigated a pre-defined set of transect lines through the area, approximately every 60 minutes, with the ADCP continuously collecting current profiles. This pattern was repeated for an approximate 12-hour duration to ensure measurements over the entire tidal cycle. The results of the data collection effort are high-resolution observations of the spatial and temporal variations in tidal current patterns throughout the survey area.

Measurements were obtained with a BroadBand 1200 kHz Acoustic Doppler Current Profiler (ADCP) manufactured by RD Instruments (RDI) of San Diego, CA. The ADCP was mounted to a specially constructed mast, which was rigidly attached to the rail of the survey vessel. The ADCP was oriented to look downward into the water column, with the sensors located approximately 1 foot below the water surface. The mounting technique assured no flow disturbance due to vessel wake.

The ADCP emits individual acoustic pulses from four angled transducers (at 20° from the vertical) in the instrument. The instrument then listens to the backscattered echoes from discrete depth layers in the water column. The difference in time between the emitted pulses and the returned echoes, reflected from ambient sound scatters (plankton, debris, sediment, etc.), is the time delay. BroadBand ADCPs measure the change in travel times from successive pulses. As particles move further away from the transducers sound takes longer to travel back and forth. The change in travel time, or propagation delay, corresponds to a change in distance between the transducer and the sound scatter, due to a Doppler shift. The propagation delay, the time lag between emitted pulses, and the speed of sound in water are used to compute the velocity of the particle relative to the transducer. By combining the velocity components for at least three of the four directional beams, the current velocities are transformed using the unit's internal compass readings to an orthogonal earth coordinate system in terms of east, north, and vertical components of current velocity.

Vertical structure of the currents is obtained using a technique called ‘range-gating’. Received echoes are divided into successive segments (gates) based on discrete time intervals of pulse emissions. The velocity measurements for each gate are averaged over a specified depth range to produce a single velocity at the specified depth interval (‘bin’). A velocity profile is composed of measurements in successive vertical bins.

The collection of accurate current data with an ADCP requires the removal of the speed of the transducer (mounted to the vessel) from the estimates of current velocity. ‘Bottom tracking’ is the strongest echo return from the emission of an additional, longer pulse to simultaneously measure the velocity of the transducer relative to the bottom. Bottom tracking allows the ADCP to record absolute versus relative velocities beneath the transducer. In addition, the accuracy of the current measurements can be compromised by random errors (or noise) inherent to this technique. Improvements in the accuracy of the measurement for each bin are achieved by averaging several velocity measurements together in time. These averaged results are termed ‘ensembles’; the more pings used in the average, the lower the standard deviation of the random error.

Current measurements were collected by the ADCP as the vessel navigated repeatedly a series of two (2) pre-defined transect lines in Sengekontacket Pond (Figure V-2). The line-cycles were repeated every hour throughout the survey. The first cycle was begun at 05:41 hours (Eastern Daylight Time, EDT) and the final cycle was completed at 5:54 hours (EDT), for a survey duration of approximately 12 hours on October 19, 2005.

The transect lines ADCP-1 and ADCP-2 were run in ascending order. These lines were designed to measure as accurately as possible the volume flux through the inlets during a complete tidal cycle. Line ADCP-1 ran across the north entrance to Sengekontacket Pond, Line ADCP-2 ran across the south entrance to inlet to Sengekontacket Pond.

V.3 HYDRODYNAMIC MODELING

The focus of this study was the development of a numerical model capable of accurately simulating hydrodynamic circulation within the Sengekontacket Pond system. Once calibrated, the model was used to calculate water volumes for selected sub-embayments as well as determine the volumes of water exchanged during each tidal cycle. These parameters are used to calculate system residence times, or flushing rates. The ultimate utility of the hydrodynamic model is to supply required input data for the water quality modeling effort described in Chapter VI.

V.3.1 Model Theory

The analysis of the Sengekontacket Pond utilized a numerical computer model to evaluate tidal and river hydraulics. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. Finite element models are well-suited to modeling estuarine and riverine areas with complex shoreline and bathymetric contours, and also allow for greater density of computational elements to be applied in areas of interest in the model domain. RMA-2 is widely accepted and tested for analyses of estuaries or rivers.

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. Graphic pre- and post-processing routines are supplied by Aquaveo through a software package called the Surface-water Modeling System or SMS. SMS is a front- and back-end software package that allows the user to easily modify model parameters (such as geometry, element coefficients, and boundary conditions), as well as view the model results and download specific data types. While the RMA model is essentially used without cost or constraint, the SMS software package requires site licensing for use.

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration
- Verification

The extent of the finite element grid was generated using digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the two entrances to Sengekontacket Pond based on the tide gauge data collected in Nantucket Sound. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several model calibration simulations for each system, 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 for the model was assisted through the use of the SMS package. The digital shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary with 4060 elements and 9378 nodes. All regions in the system were represented by two-dimensional (depth-averaged) elements. The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties within the estuary. Fine resolution was required to simulate the channel constrictions that significantly impact the estuarine hydrodynamics. The completed grid is made up of quadrilateral and triangular two-dimensional elements. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the recent field surveys and the NOAA survey offshore of Sengekontacket Pond. The final interpolated grid bathymetry is shown in Figure V-9. The model computed water elevation and velocity at each node in the model domain.

Figure V-8. The model finite element mesh developed for Sengekontacket Pond system. The model seaward boundaries were specified with forcing functions consisting of water elevation measurements obtained in Nantucket Sound.

Grid resolution is governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each region. Smaller cross channel node spacing in the navigation channels was designed to provide a more detailed analysis in these regions of rapidly varying velocities and bathymetry. Widely spaced nodes were utilized in areas where velocity gradients were likely to be less acute; for example, on marsh plains and in broad, shoal sections in the model domain. 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

Three types of boundary conditions were employed for the RMA-2 model: 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

The model was forced at the open boundaries using water elevations measurements obtained in Nantucket Sound (described in section V.2.2). These measured time series consists of all physical processes affecting variations of water level: tides, winds, and other non-tidal oscillations of the sea surface. In addition the phasing difference between the north and south inlets. The rise and fall of the tide in Nantucket Sound is the primary driving force for estuarine circulation. Dynamic (time-varying) model simulations specified a new water surface elevation at each of the offshore boundaries every 10 minutes. The model specifies the water elevation at the offshore boundaries, and uses these values to calculate water elevations at every nodal point within the system, adjusting each value according to solutions of the model equations. Changing water levels in Nantucket Sound produce variations in surface slopes within the estuary; these slopes drive water either into the system (if water is higher offshore) or out of the system (if water levels fall in the pond).

V.3.3 Calibration

After developing the finite element grid and specifying boundary conditions, the model was calibrated. Calibration ensured the model predicts accurately what was observed during the field measurement program. Numerous model simulations were required to calibrate the model, with each run varying specific parameters such as friction coefficients, turbulent exchange coefficients, fresh water inflow, and subtle modifications to the system bathymetry to achieve a best fit to the data.

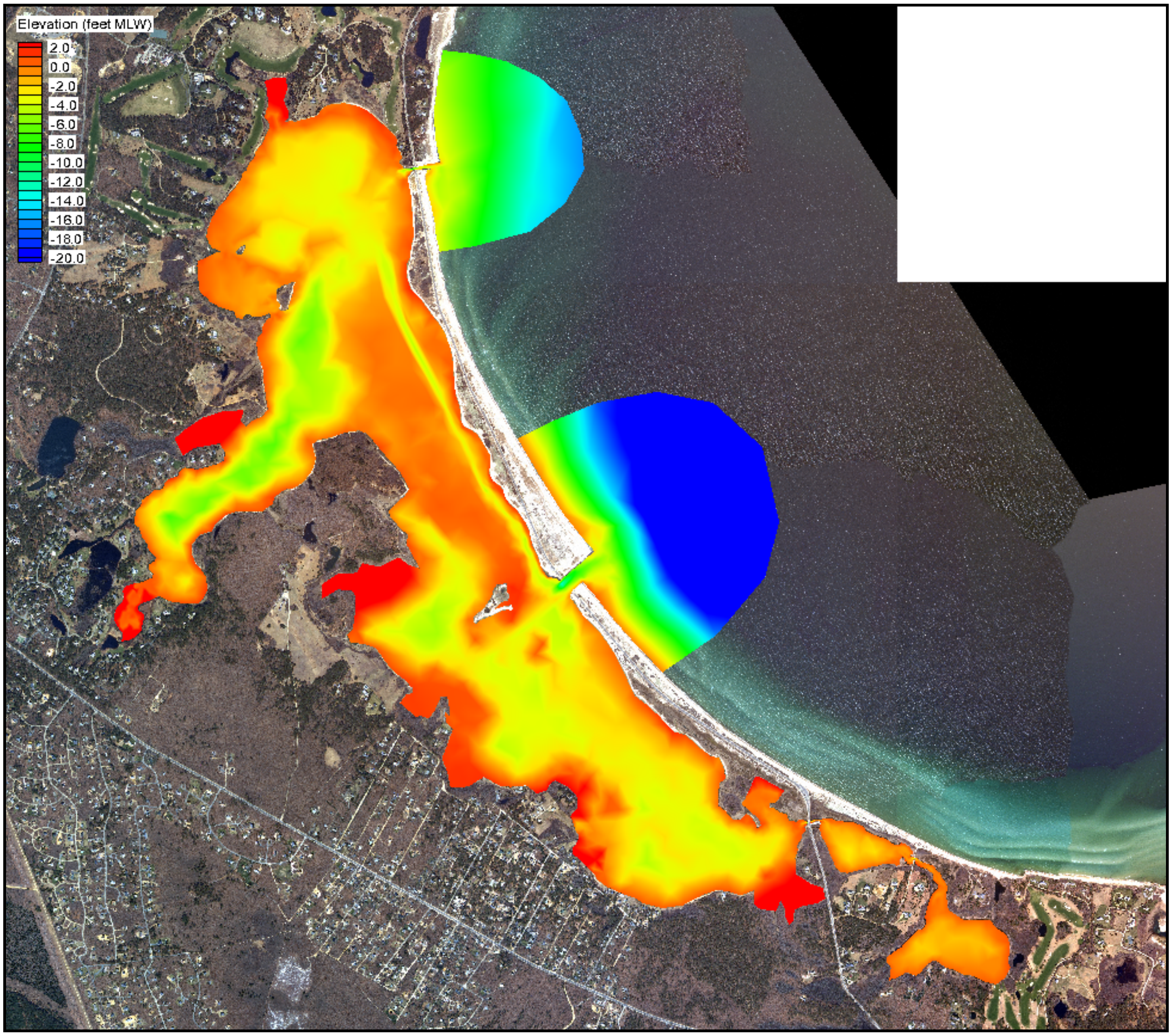

Figure V-9. Depth contours of the completed Sengekontacket Pond finite element mesh.

Calibration of the flushing model required a close match between the modeled and measured tides in each of the sub-embayments where tides were measured. Initially, the model was calibrated by the visual agreement between modeled and measured tides. To refine the calibration procedure, water elevations were output from the model at the same locations in the estuary where tide gauges were installed, and the data were processed to calculate standard error as well harmonic constituents (of both measured and modeled data) over the seven-day calibration period. The amplitude and phase of four constituents (M_2, M_4, M_6, and K_1) were compared and the corresponding errors for each were calculated. The intent of the calibration procedure is to minimize the error in amplitude and phase of the individual constituents. In general, minimization of the M_2 amplitude and phase becomes the highest priority, since this is the dominant constituent. Emphasis is also placed on the M_4 constituent, as this constituent has the greatest impact on the degree of tidal distortion within the system, and provides the unique shape of the modified tide wave at various points in the system.

The calibration was performed for an approximate nine-day period, beginning 1900 hours EST November 9, 2005 and ending 1900 EST November 18, 2005. This time period included a

29-hour model spin-up period, and a 15-tide cycle period used for calibration. This representative time period was selected because it included tidal conditions where the wind-induced portion of the signals (i.e. the residual) was minimal, hence more typical of tidal circulation within the estuary. The selected time period also spanned the transition from neap (bi-monthly minimum) to spring (bi-monthly maximum) tide ranges, which is representative of average tidal conditions in the embayment system. Throughout the selected 7.75 day period, the tide ranged approximately 3.5 feet from minimum low to maximum high tides. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. Modeled tides were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.3.3.1 Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where water depths can become shallow and velocities relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude attenuation and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient. First, Manning's friction coefficient values of 0.025 were specified for all elements. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels with pools and shoals with higher friction (Henderson, 1966). On the marsh plains around the perimeter of the system, damping of flow velocities typically is controlled more by “form drag” associated with marsh plants than the bottom friction described above. However, simulation of this “form drag” is performed using Manning’s coefficients as well, with values ranging from 2-to-10 times friction coefficients used in sandy channels. Final calibrated friction coefficients (listed in Table V-5, corresponding to the delineations shown in Figure V-8) were largest for marsh plain area, where values were set at 0.033. Small changes in these values did not change the accuracy of the calibration.

Table V-5. Manning’s Roughness coefficients used in simulations of modeled embayments.

Embayment	Bottom Friction
Nantucket Sound	0.025
North Inlet	0.025
South Inlet	0.025
Sengekontacket Pond	0.025
Marsh	0.033
Trapps Pond - North	0.027
Trapps Pond - South	0.026
Culvert 1 - Edgartown Oak Bluffs Road	0.033
Culvert 2 - Cow Bay Road	0.033
Sengekontacket Pond Shallows	0.026

V.3.3.2 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 swift, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). The model was mildly sensitive to turbulent exchange coefficients, with areas of marsh plain being most sensitive. In other regions where the flow gradients were not as strong, the model was much less sensitive to changes in the turbulent exchange coefficients. Typically, model turbulence coefficients (D) are set between 50 and 100 lb-sec/ft^2 (as listed in Table V-6). Higher values (up to 500 lb-sec/ft^2) are used on the marsh plain, to ensure solution stability.

Table V-6. Turbulence exchange coefficients (D) used in simulations of modeled embayment system.

Embayment	D (lb-sec/ft$^{2)}$
Nantucket Sound	20
North Inlet	20
South Inlet	20
Sengekontacket Pond	30
Marsh	145
Trapps Pond - North	35
Trapps Pond - South	20
Culvert 1 - Edgartown Oak Bluffs Road	75
Culvert 2 - Cow Bay Road	50
Sengekontacket Pond Shallows	50

V.3.3.3 Wetting and Drying/Marsh Porosity Processes

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

V.3.3.4 Comparison of Modeled Tides and Measured Tide Data

Several calibration model runs were performed to determine how changes to various parameters (e.g. friction and turbulent exchange coefficients) affected the model results. These trial runs achieved excellent agreement between the model simulations and the field data. Comparison plots of modeled versus measured water levels at the six gauge locations within Sengekontacket Pond and the two offshore gauges are presented in Figures V-10 through V-17. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the calibration time period are shown in Table V-7. The constituent values in for the calibration time period differ from those in Tables V-2 because constituents were computed for only 7.75 days, rather than the entire 34-day period represented in Tables V-2. Errors associated with tidal constituent height were on the order of hundredths of feet, which was an order of magnitude better than the accuracy of the tide gage gauges (±0.12 ft). Time lag errors were less than the time increment resolved by the model and measured tide data (1/6 hours or 10 minutes), indicating good agreement between the model and data.

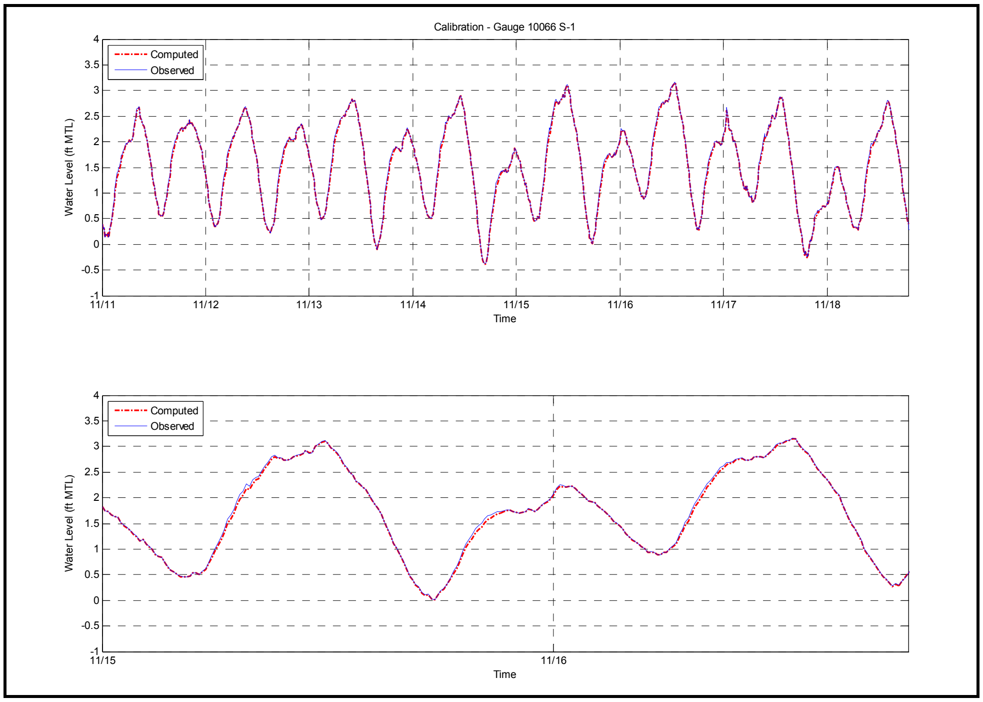

Figure V-10. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the calibration time period, for the offshore gauging station S-1. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

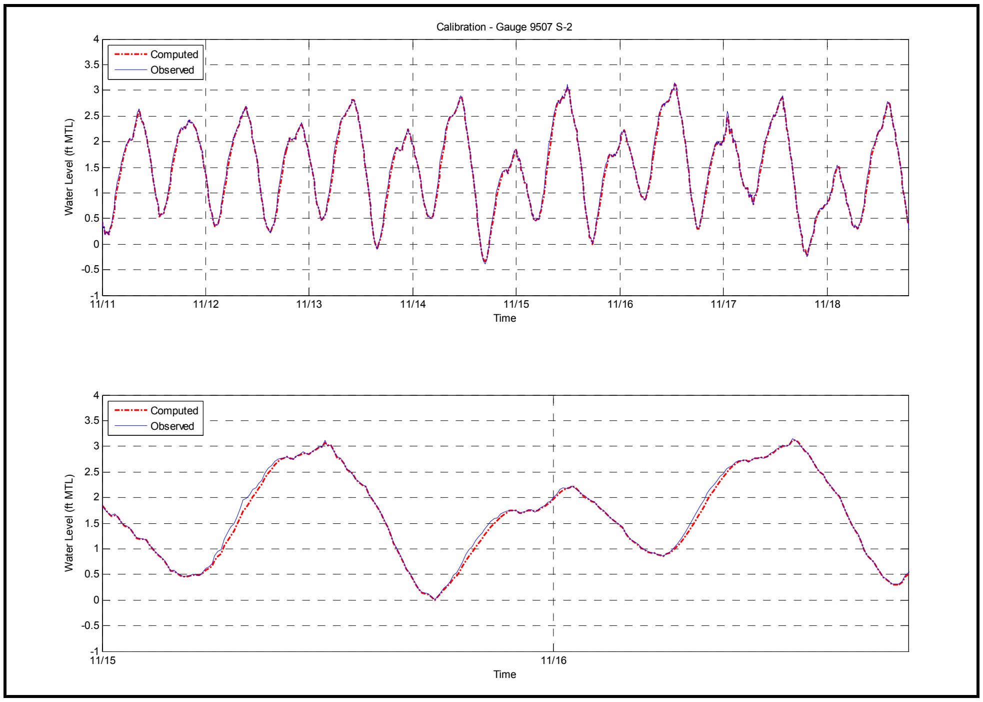

Figure V-11. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the calibration time period, for the offshore gauging station S-2. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

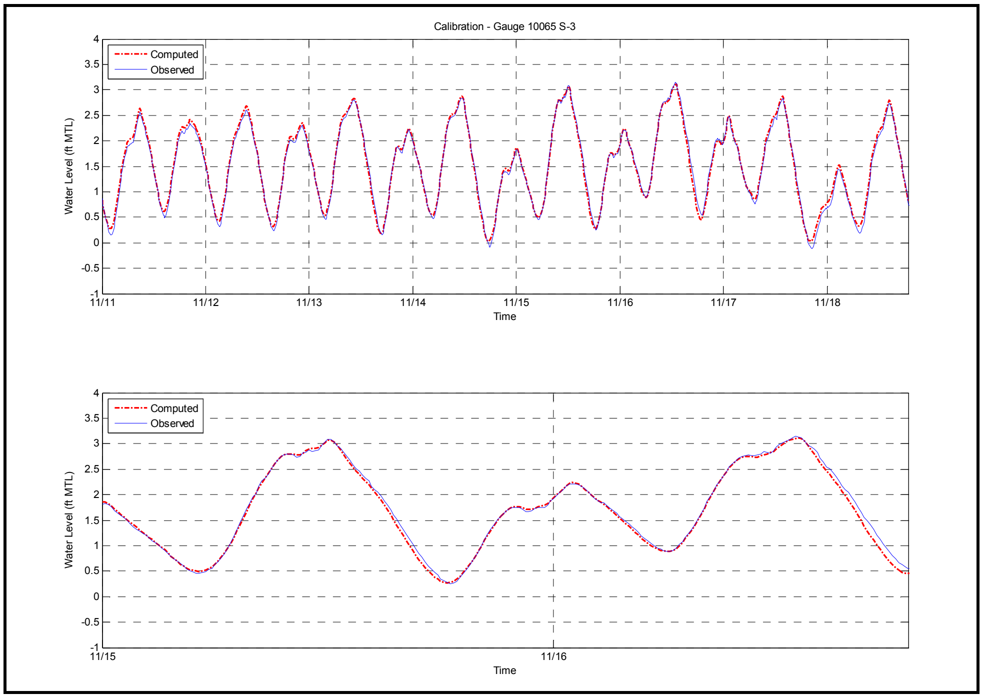

Figure V-12. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the calibration time period at the northern inlet gauging station S-3. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

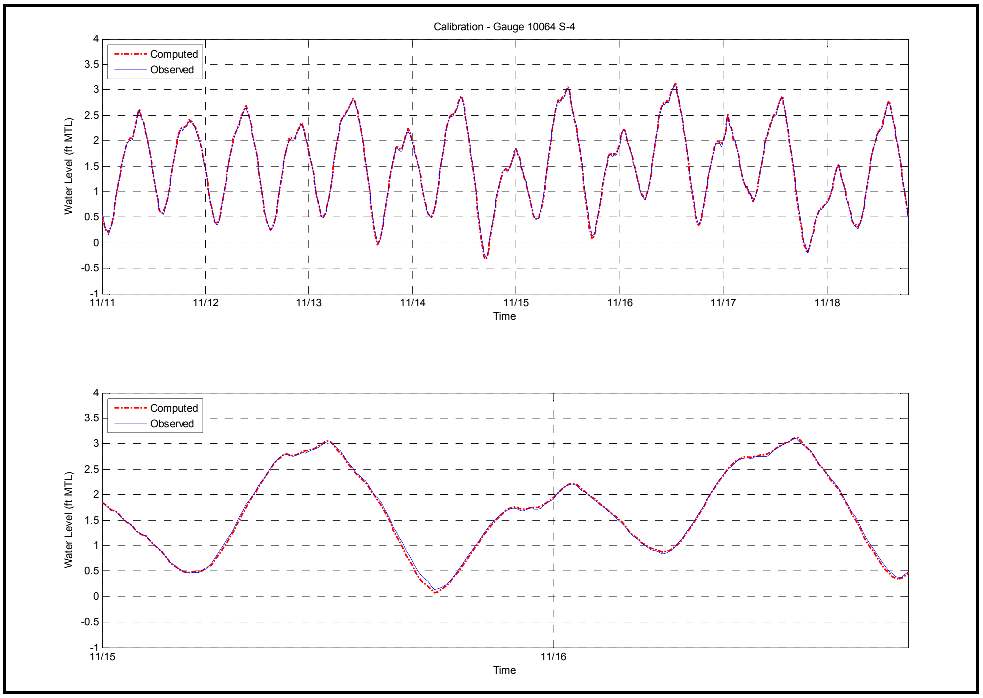

Figure V-13. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the calibration time period at the southern inlet gauging station S-4. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

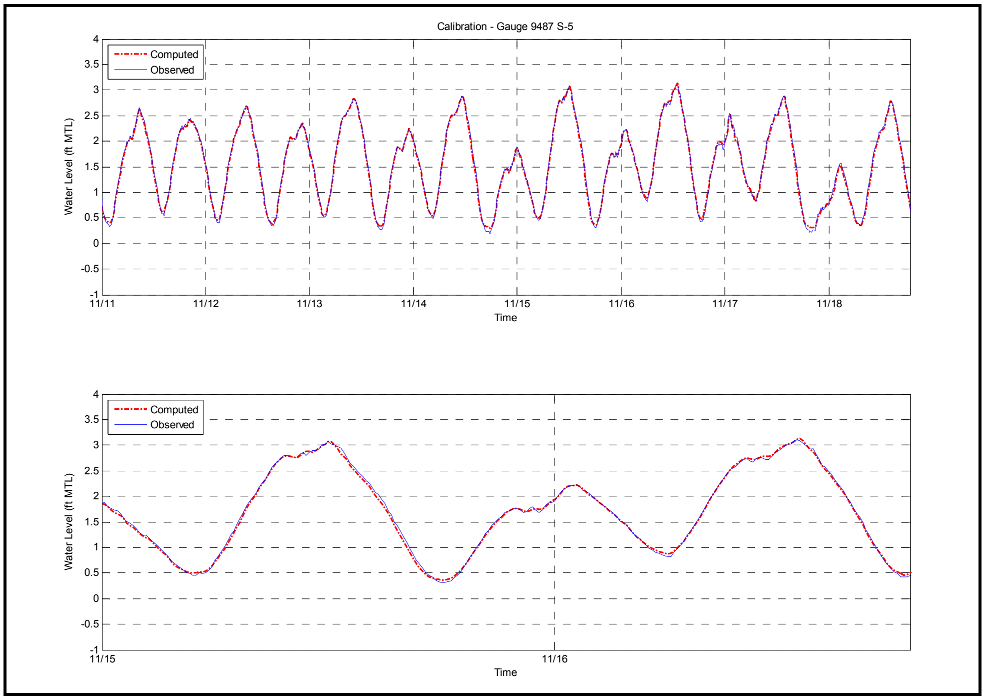

Figure V-14. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the southern gauging station In Sengekontacket Pond S-5. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

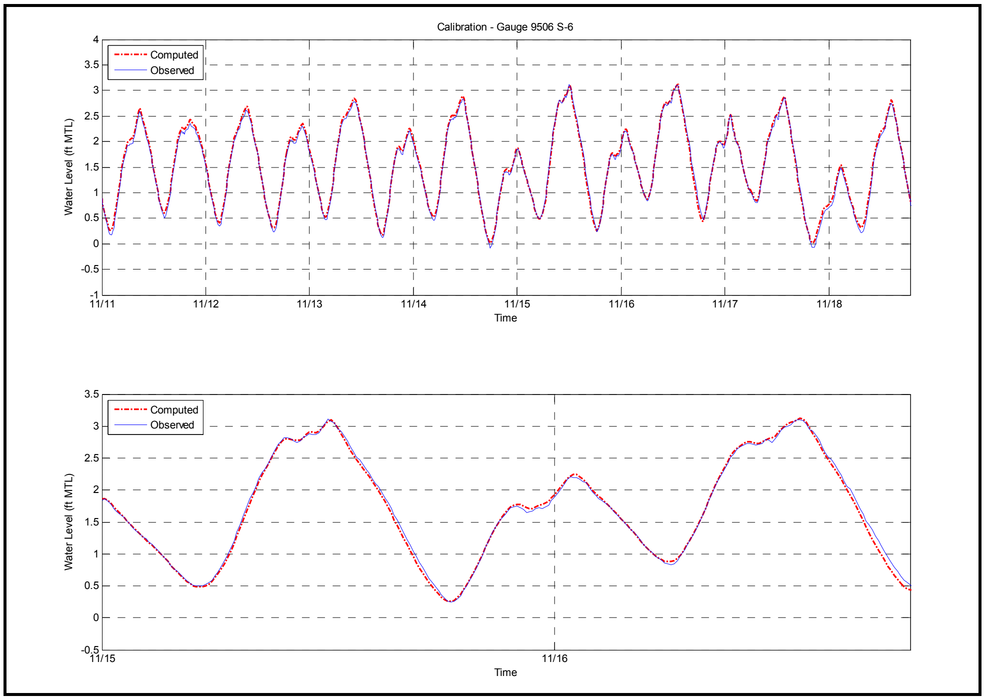

Figure V-15. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period for the Majors Cove gauging station S-6. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

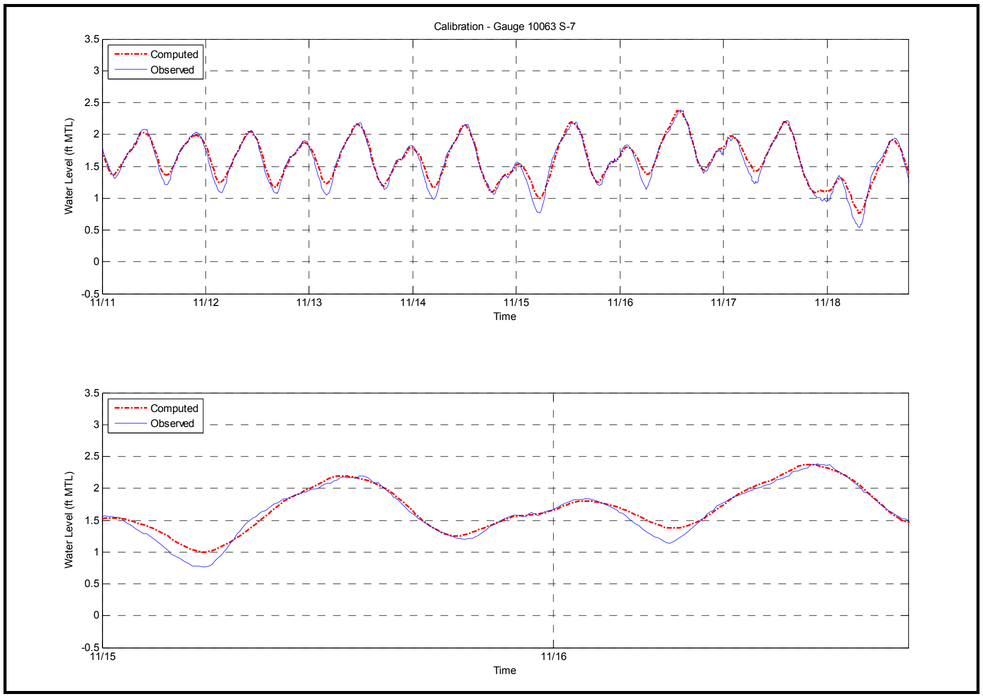

Figure V-16. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the northern Trapps Pond gauging station S-7. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

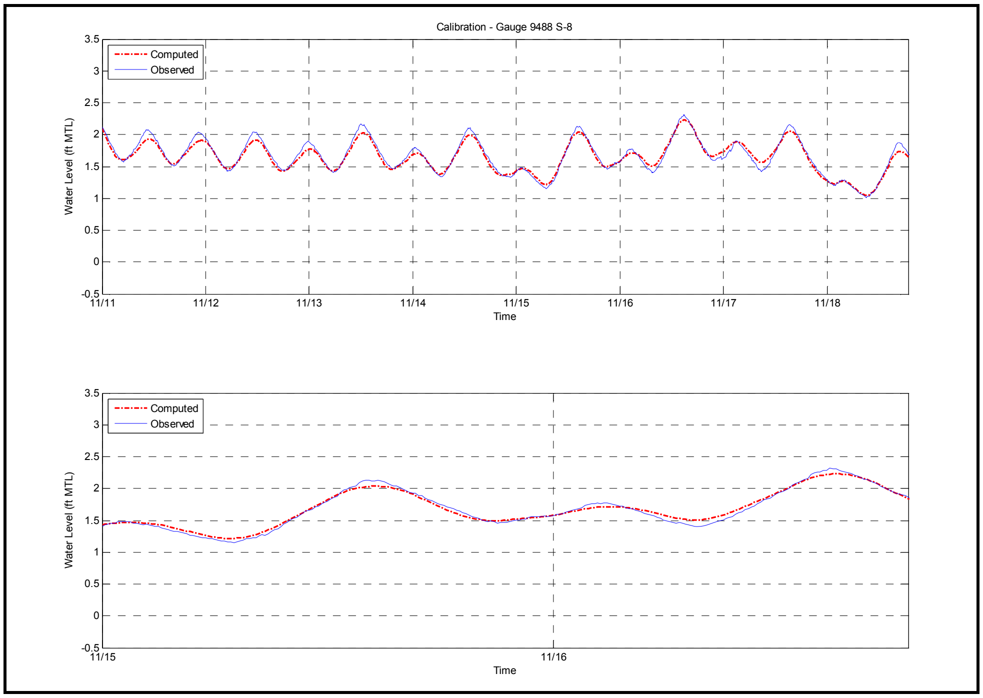

Figure V-17. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the southern Trapps Pond gauging station S-8. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

Table V-7. Comparison of Tidal Constituents calibrated RMA2 model versus measured tidal data for the period November 11 to November 18, 2005.

Model Verification Run

Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Nantucket Sound S-1	0.36	0.96	0.23	0.08	-137.17	-120.21
Nantucket Sound S-2	0.35	0.98	0.18	0.05	-132.02	-112.92
North Inlet S-3	0.36	0.94	0.14	0.08	-122.31	-79.29
South Inlet S-4	0.36	0.97	0.17	0.06	-127.87	-101.54
Sengekontacket Pond S-5	0.34	0.91	0.15	0.06	-125.93	-100.39
Majors Cove S-6	0.36	0.94	0.14	0.09	-121.45	-75.54
Trapps Pond North S-7	0.16	0.33	0.05	0.01	-93.88	-71.28
Trapps Pond South S-8	0.12	0.19	0.01	0.01	-47.95	-9.34

Measured Tidal Data

Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Nantucket Sound S-1	0.37	0.96	0.24	0.10	-138.88	-121.6
Nantucket Sound S-2	0.36	0.98	0.20	0.07	-134.67	-116.16
North Inlet S-3	0.37	0.93	0.15	0.10	-120.74	-70.48
South Inlet S-4	0.36	0.96	0.18	0.07	-128.14	-100.68
Sengekontacket Pond S-5	0.36	0.92	0.17	0.07	-125.5	-96.49
Majors Cove S-6	0.37	0.92	0.15	0.10	-120.52	-70.25
Trapps Pond North S-7	0.18	0.37	0.07	0.03	-100.07	-84.07
Trapps Pond South S-8	0.15	0.23	0.01	0.02	-48.95	-102.67

Error

Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Nantucket Sound S-1	0.01	0.00	0.01	0.01	-3.53	-1.45
Nantucket Sound S-2	0.01	-0.01	0.02	0.02	-5.48	-3.36
North Inlet S-3	0.01	-0.01	0.01	0.02	3.25	9.12
South Inlet S-4	0.01	-0.01	0.01	0.02	3.25	9.12
Sengekontacket Pond S-5	0.02	0.01	0.02	0.01	0.87	4.03
Majors Cove S-6	0.01	-0.01	0.01	0.01	1.92	5.48
Trapps Pond North S-7	0.03	0.04	0.02	0.01	-12.8	-13.25
Trapps Pond South S-8	0.03	0.04	0.00	0.01	-2.07	-96.61

V.3.4 ADCP verification of the Sengekontacket Pond system

An additional model verification check was possible by using collected ADCP velocity data to verify the performance of the model in representing the system dynamics. Computed flow rates from the model were compared to flow rates determined using the measured velocity data. The ADCP data survey efforts are described in Section V.2.3. For the model ADCP verification, the Sengekontacket Pond model was run for the period covered during the ADCP survey on October 19, 2005.

The verification model period was performed for an approximate eight-day period, beginning 0000 hours EDT October 18, 2005 and ending 0000 EDT October 27, 2005. This time period included a 24-hour model spin-up period, and a tide cycle period used to compare to the ADCP data. Model flow rates were computed in RMA-2 at continuity lines (channel cross-sections) that correspond to the actual ADCP transects followed in the survey across the two inlets to Sengekontacket Pond.

Data comparisons at the Sengekontacket Pond ADCP transects show good agreement with the model predictions, with R^2 correlation coefficients between data and model results range from 0.95 to 0.91. A comparison of the measured and modeled volume flow rates at the survey transect are shown in Figures V-18 through V-19. The top plot in the figure shows the flow comparison, and the lower plot shows the time series of tide elevations for the same period. Each ADCP point (black stars shown on the plots) is a summation of flow measured along the ADCP transect at a discrete moment in time. The ‘bumps’ and ‘skips’ of the flow rate curve (more evident in the model output) can be attributed mostly to the peculiar nature of the forcing tide in this region, but also to the effects of winds (i.e., atmospheric effects) on the water surface and friction across the seabed periodically retarding or accelerating the flow through the inlets. If water surface elevations changed smoothly as a sinusoid, the volume flow rate would also appear as a smooth curve. However, since the rate at which water surface elevations change does not vary smoothly, the flow rate curve is expected to show short-period fluctuations.

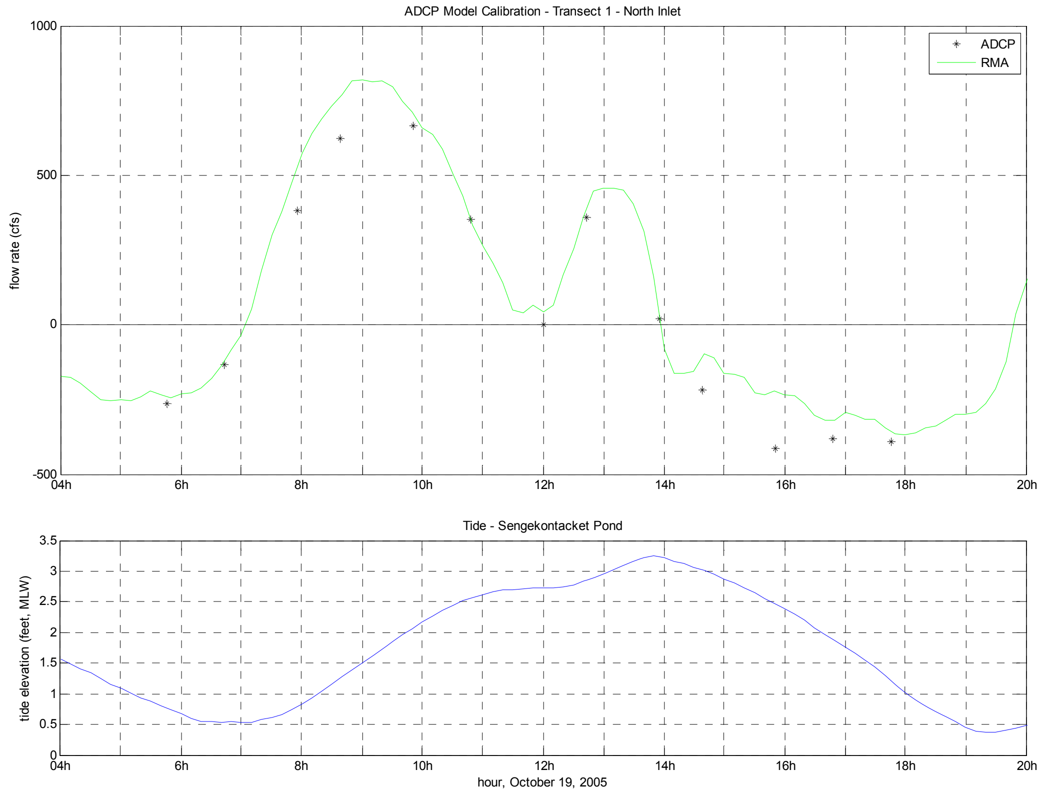

Figure V-18. Comparison of measured volume flow rates versus modeled flow rates (top plot) across northern entrance to Sengekontacket Pond (transect ADCP-1), over a tidal cycle on October 19, 2005 (R^2 = 0.95). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Nantucket Sound.

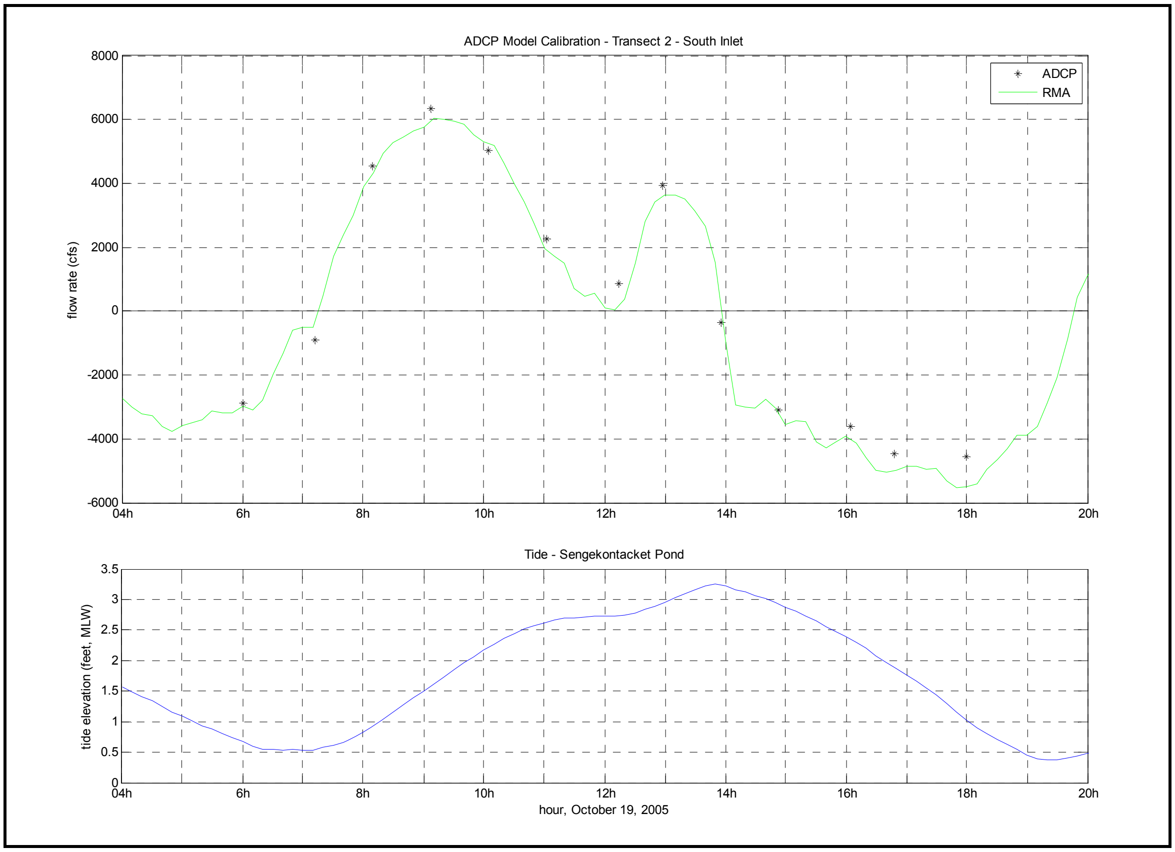

Figure V-19. Comparison of measured volume flow rates versus modeled flow rates (top plot) across the southern entrance to Sengekontacket Pond (transect ADCP-2), over a tidal cycle on October 19, 2005 ($R^2 = 0.96$). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Nantucket Sound.

V.3.5 Model Circulation Characteristics

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

From the model runs of Sengekontacket Pond and the ADCP data, it is clear that the southern inlet to Sengekontacket Pond conveys a majority of the tidal flow into and out of the system. The southern inlet conveys approximately 85% of the total flow into the system on a flood tide, with the remaining passing through the northern inlet. The maximum flood and ebb velocities are higher in the northern inlet than the southern inlet due to the shallow bathymetry accelerating flow through the northern inlet. A close-up of the model output is presented in Figure V-20, which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow, for a single model time-step, at the portion of the tide where maximum flood velocities occur at the inlet.

The hydraulic model shows that the culverts conveying tidal flows into and within Trapps Pond represent significant restrictions to the natural flow. The limited size of the culverts restricts the full hydraulic exchange of tidal waters between the main basin and the pond. The tide range within Trapps Pond is approximately third of the tide range in Sengekontacket Pond. One option to restore full tidal exchange into Trapps pond would be to increase the size of the culvert under Edgartown Oak Bluffs Road.

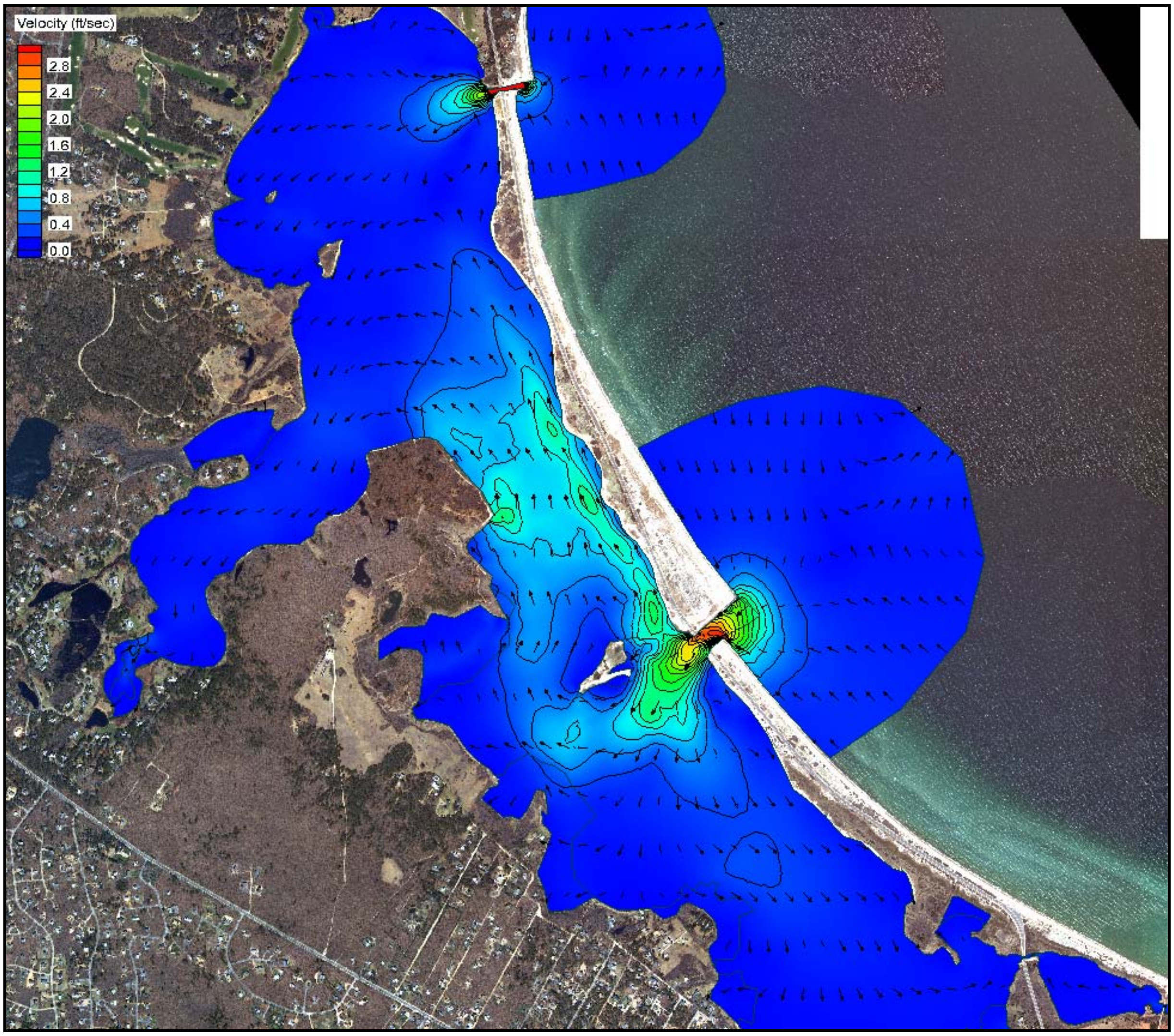

Figure V-20. Example of hydrodynamic model output in Sengekontacket Pond for a single time step where maximum flood velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

V.5 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through each inlet, the primary mechanism controlling estuarine water quality within Sengekontacket Pond is tidal exchange. A rising tide offshore in Nantucket Sound creates a slope in water surface from the ocean into the Sengekontacket Pond. Consequently, water flows into (floods) the system. Similarly, the estuary drains into the open waters of the Sound 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 embayment to the entrance of the system. System residence times are computed as follows:

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

where T_{system} denotes the residence time for the system, V_{system} represents volume of the (entire) system at mean tide level, P equals the tidal prism (or volume entering the system through a single tidal cycle), and t_{cycle} the period of the tidal cycle, typically 12.42 hours (or 0.52 days). To compute system residence time for a sub-embayment, the tidal prism of the sub-embayment replaces the total system tidal prism value in the above equation.

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using Trapps Pond as an example, the **system residence time** is the average time required for water to migrate from the pond, through the culvert and into Sengekontacket Pond and out the inlet, where the **local residence time** is the average time required for water to migrate from Trapps Pond into Sengekontacket Pond (not all the way to through inlet and out of the system). Local residence times for each sub-embayment are computed as:

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

where T_{local} denotes the residence time for the local sub-embayment, V_{local} represents the volume of the sub-embayment at mean tide level, P equals the tidal prism (or volume entering the local sub-embayment through a single tidal cycle), and t_{cycle} the period of the tidal cycle (again, 0.52 days).

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

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. 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 a total nitrogen dispersion model (Section VI). The water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Sengekontacket Pond and its component sub-embayments.

The volume of the each sub-embayment, as well as their respective tidal prisms, were computed as cubic feet (Table V-8). Model divisions used to define the system sub-embayments for the systems include 1) all of Sengekontacket Pond (including all sub-embayments), 2) Majors Cove, and 3) Trapps Pond. The model computed total volume of each sub-embayment, at every time step, and this output was used to calculate mean sub-embayment volume and average tide prism. Since the 7.75-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-8. Embayment mean volumes and average tidal prisms of the Sengekontacket Pond system during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Sengekontacket Pond with sub-embayments	136,846,221	91,010,245
Majors Cove	12,109,887	10,247,168
Trapps Pond	5,982,613	1,297,450

Residence times were averaged for the tidal cycles comprising a representative 7.75 day period (15 tide cycles), and are listed in Table V-9. Residence times were computed for the entire estuary, as well selected sub-embayments within the two systems. 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 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 use and computation of Residence Time is discussed on the previous pages. 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.

Table V-9. Computed System and Local residence times for sub-embayments of the Sengekontacket Pond system.

Embayment	System Residence Time (days)	Local Residence Time (days)
Sengekontacket Pond with sub-embayments	0.8	0.8
Majors Cove	6.9	0.6
Trapps Pond	54.8	2.4

The whole of Sengekontacket Pond system has a low residence time (0.8 days) showing that the system has good flushing conditions. This is also true of Majors Cove. The only embayment with moderately high local residence time (2.4 days) is Trapps Pond. The flow into and out of Trapps Pond is restricted by the narrow culvert and channel under Edgartown Oak Bluffs Road. The longer residence times suggest that the water quality within the Trapps Pond is highly sensitive to the combined nutrient load input from the system watersheds, benthic sediments and direct atmospheric deposition. The system residence time for Trapps Pond does not provide a good indication of the water quality since the variation in basin volumes from Trapps Pond to the system volume is considerable. The result is a very long system residence time which should not be considered an accurate characterization of the conditions occurring in the pond. A more thorough examination of nutrient loading is required to provide an accurate characterization (see Section 6).

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

Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. However, water exiting a small sub-embayment on a relatively calm day may not completely mix with estuarine waters. In this case, the “strong littoral drift” assumption would lead to an under-prediction of residence time. Since littoral drift in Nantucket Sound typically is strong because of the effects of the local winds, tidal induced mixing, the “strong littoral drift” assumption should cause 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 Sengekontacket Pond System. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayment

Extensive field measurements and hydrodynamic modeling of the embayment were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated model output representing the transport of water within the system embayment. Files of node locations and node connectivity for the RMA-2 model grid 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 a 11-tidal cycle period in November 2005. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow for the model to reach a dynamic “steady state”, and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayment

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

VI.1.3 Measured Nitrogen Concentrations in the Embayment

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in Figure VI-1. The multi-year averages present the “best” comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data is the minimum required to provide a baseline for MEP analysis. Six years of data (collected between 2003 and 2009) were available for stations monitored by SMAST in the Sengekontacket Pond System.

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 Sengekontacket Pond 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 the Sengekontacket Pond System. Like RMA-2 numerical code,

Table VI-1. Sengekontacket Pond water quality monitoring data, and modeled Nitrogen concentrations for the Sengekontacket Pond System used in the model calibration plots of Figure VI-2. All concentrations are given in mg/L N. “Data mean” values are calculated as the average of the separate yearly means.

Sub-Embayment	Farm Neck Inlet	Farm Neck Basin	Majors Cove	Majors Cove	Main Inlet	Ocean Heights	Ocean Heights	Ocean Heights	Trapps Pond
Monitoring station	Skt-1	Skt-2	Skt-3	Skt-4	Skt-5	Skt-6	Skt-7	Skt-8	Skt-9
2003 mean	0.457	0.451	0.554	0.611	0.306	0.365	0.420	0.604	0.607
2004 mean	0.350	0.369	0.416	0.366	0.288	0.315	0.299	0.417	0.413
2005 mean	0.268	0.285	0.351	0.356	0.205	0.268	0.217	0.311	0.396
2006 mean	0.351	0.373	0.421	0.437	0.355	0.319	0.312	0.412	0.516
2007 mean	0.348	0.336	--	0.392	0.257	0.259	0.279	0.380	--
2008 mean	0.402	0.365	0.347	0.373	0.336	0.270	0.429	0.381	0.380
2009 mean	0.295	0.294	0.342	0.347	0.248	0.264	0.263	0.378	0.422
mean	0.351	0.347	0.414	0.406	0.290	0.302	0.314	0.392	0.445
s.d. all data	0.073	0.064	0.098	0.100	0.071	0.083	0.104	0.094	0.089
N	24	24	25	25	25	25	27	24	20
model min	0.295	0.312	0.340	0.370	0.294	0.300	0.299	0.323	0.331
model max	0.324	0.328	0.363	0.380	0.320	0.325	0.317	0.337	0.476
model average	0.308	0.320	0.351	0.375	0.299	0.308	0.306	0.331	0.382

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 in Falmouth (Ramsey *et al*., 2000); Mashpee, MA (Howes *et al*., 2004) and Chatham, MA (Howes *et al*., 2003).

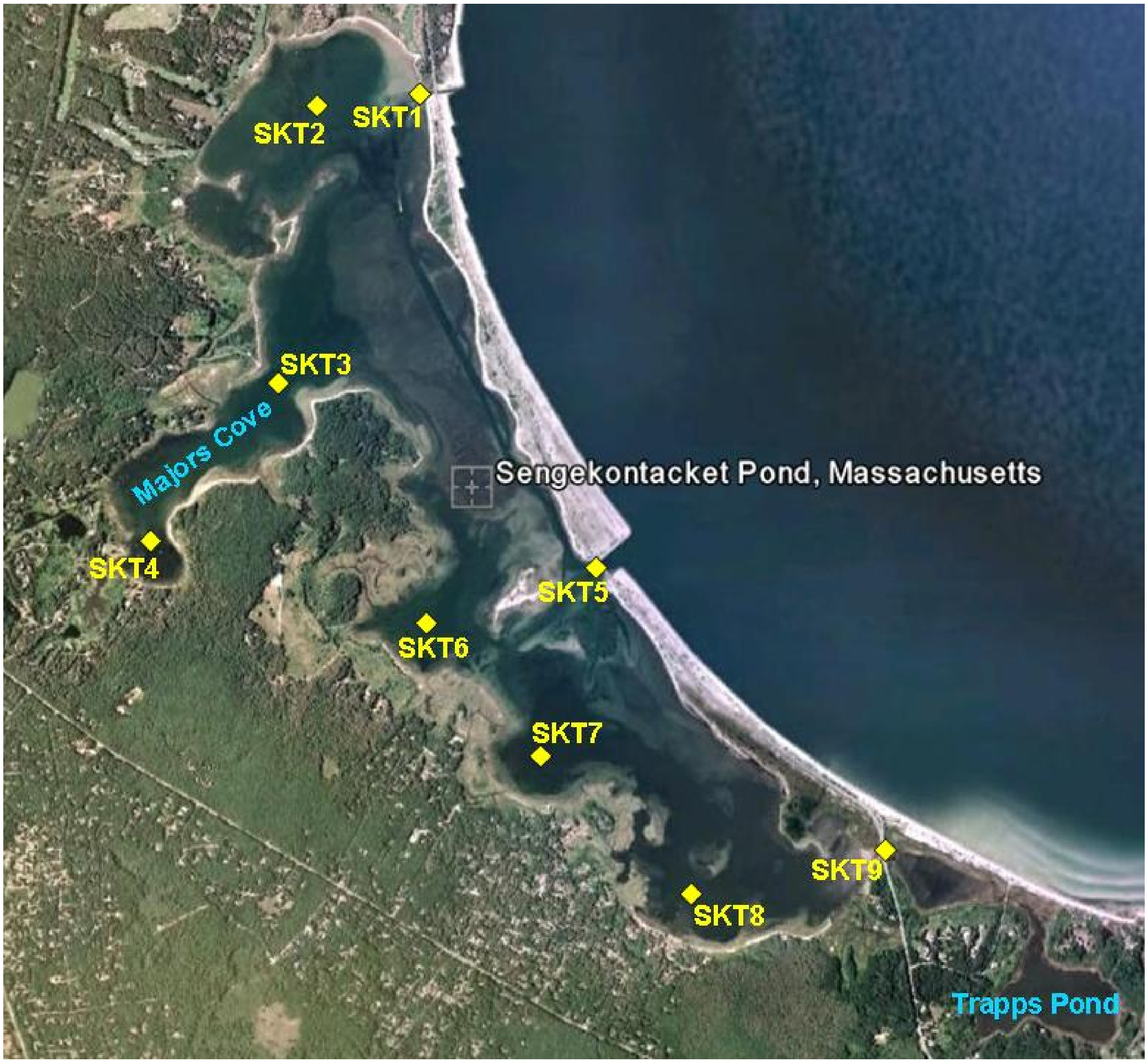

Figure VI-1. Estuarine water quality monitoring station locations in the Sengekontacket Pond System. Station labels correspond to those provided in Table VI-1.

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 SMAST and Martha's Vineyard Commission watershed loading analysis (based on the Martha's Vineyard Commission watersheds), as well as the measured bottom sediment nitrogen fluxes.

Water column nitrogen measurements were utilized as model boundaries and as calibration data. Hydrodynamic model output (discussed in Section V) provided the remaining information (tides, currents, and bathymetry) needed to parameterize the water quality model of the system.

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 Sengekontacket Pond System.

VI.2.2 Water Quality Model Setup

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

Based on groundwater recharge rates from the SMAST and Martha's Vineyard Commission, the hydrodynamic model was set-up to include ground water flowing into the system from the watersheds. Majors Cove along with Fresh Pond watersheds has groundwater flow rate into the system is 419,009 ft^3/day (11,865 m^3/day), Ocean Heights watershed has a groundwater flow rate of 394,409 ft^3/day (11,168 m^3/day), Farm Neck watershed has a groundwater flow rate of 316,744 ft^3/day (8,969 m^3/day), Trapp's Pond has a groundwater flow rate of 112,715 ft^3/day (3,192 m^3/day), and State Beach watershed has a groundwater flow rate of 24,310 ft^3/day (688 m^3/day).

For the model, an initial total N concentration equal to the concentration at the open boundaries 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 5 tidal-day (125 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 Sengekontacket Pond System.

VI.2.3 Boundary Condition Specification

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

The loadings used to model present conditions in Sengekontacket Pond System are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For present conditions, the benthic flux is relatively low or negative indicating a net uptake of nitrogen in the bottom sediments. Trapp's Pond is the only sub-embayment with a benthic regeneration loading rate approaching the watershed load.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Farm Neck	9.392	3.337	-0.896
Majors Cove	11.627	1.189	5.117
Ocean Heights	13.260	5.932	-15.712
Trapps Pond	3.175	0.660	3.276
State Beach	0.115	-[1]	1.707

[1] Atmospheric deposition for State Beach is including within the atmospheric disposition for Ocean Heights

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundaries were specified. The model uses concentrations at the open boundaries during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundaries. The boundary concentrations in Nantucket Sound were set at 0.294 mg/L, based on SMAST data from the Nantucket Sound. The open boundaries total nitrogen concentration represents long-term average summer concentrations found within Nantucket Sound.

VI.2.4 Model Calibration

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

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

Embayment Division	E m^2/sec
Nantucket Sound	10.0
Inlet - North	5.0
Inlet - South	5.0
Sengekontacket Pond	5.0
Marsh	1.5
Trapps Pond - North	5.0
Trapps Pond - South	5.0
Culvert 1	6.0
Culvert 2	6.0
Sengekontacket Shallows	2.0
Majors Cove	6.5
Farm Neck	5.0
Mid Basin	5.0

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

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

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

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for the system. The model fit is exceptional for the Sengekontacket Pond System, with rms error of 0.02 mg/L and an R^2 correlation coefficient of 0.99.

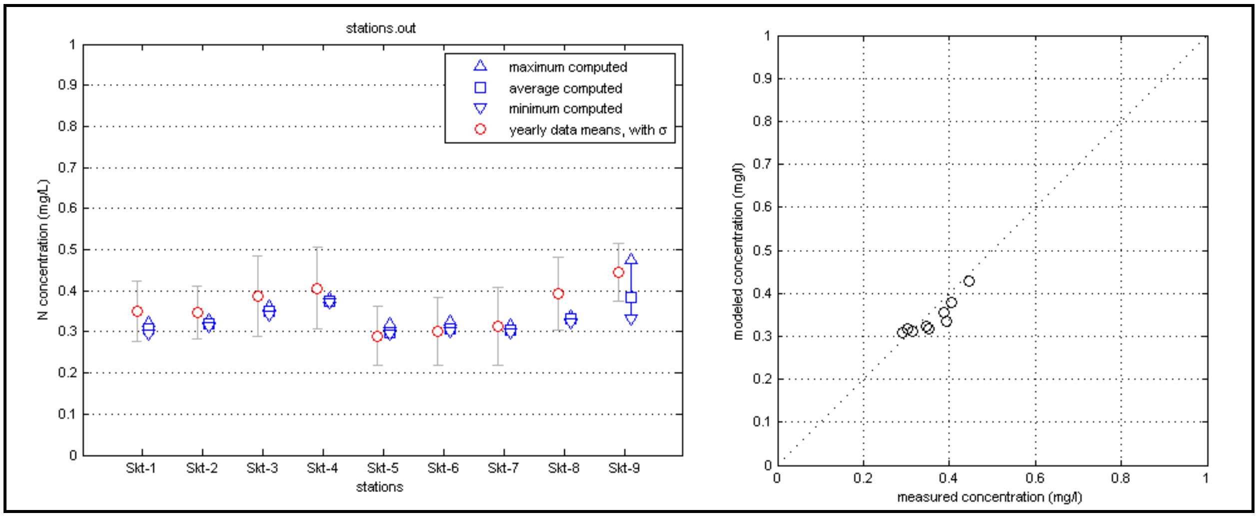

Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Sengekontacket Pond System. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line.

A contour plot of calibrated model output is shown in Figure VI-4 for Sengekontacket Pond System. In the figure, color contours indicate nitrogen concentrations throughout the model domain. The output in the figure show average total nitrogen concentrations, computed using the full 5-tidal-day model simulation output period.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Sengekontacket Pond 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, and groundwater inputs. The open boundary salinity was set at 30.0 ppt. For groundwater inputs salinities were set at 0 ppt. The total groundwater input used for the model was 1,267,187 ft^3/day (35,883 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed evenly within each watershed through grid cells that formed the perimeter along each watershed’s land boundary.

Comparisons of modeled and measured salinities are presented in Figure VI-5, with contour plots of model output shown in Figure VI-6. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in Sengekontacket Pond System. The rms error of the models was 0.95 ppt, and correlation coefficient was 0.99. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical systems.

Figure VI-4. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for Sengekontacket Pond System. The approximate locations of the sentinel threshold stations for Sengekontacket Pond System (SKT-4 and SKT-9) are shown.

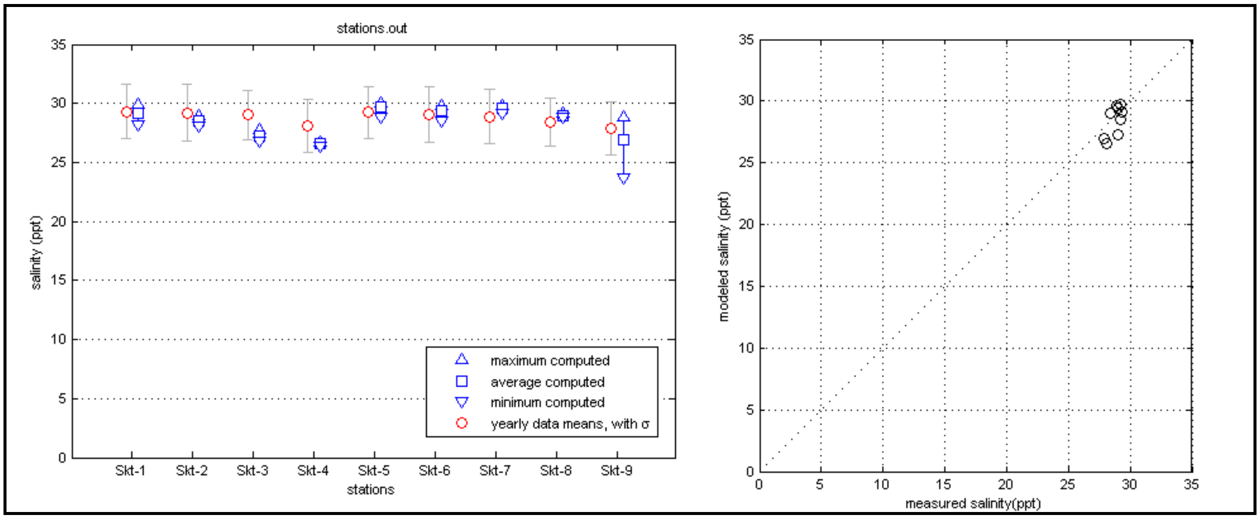

Figure VI-5. Comparison of measured and calibrated model output at stations in Sengekontacket Pond System. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (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. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line.

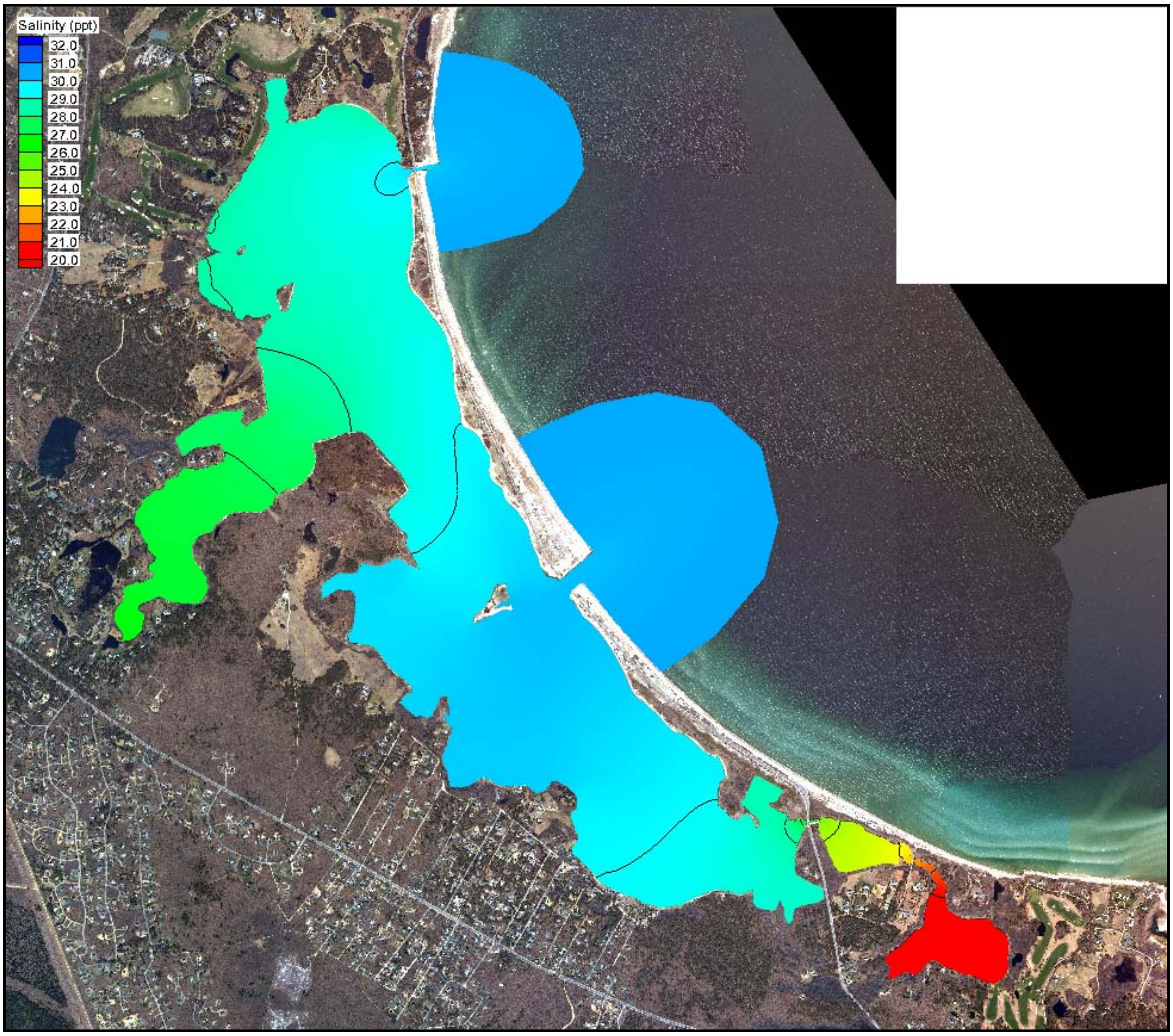

Figure VI-6. Contour plots of modeled salinity (ppt) in Sengekontacket Pond System.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Sengekontacket Pond 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
Farm Neck	9.392	10.926	+16.3%	0.647	-93.1%
Majors Cove	11.627	13.003	+11.8%	1.093	-90.6%
Ocean Heights	13.260	19.962	+50.5%	0.792	-94.0%
Trapps Pond	3.175	6.148	+93.6%	0.238	-92.5%
State Beach	0.115	0.115	+0.0%	0.049	-57.1%

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be more than a significant increase in watershed nitrogen load to the Sengekontacket Pond as a result of potential future development. Specific watershed areas would experience significant load increases, for example the loads to Trapps Pond would increase 93% from the present day loading levels. For the no load scenarios, a majority of the load entering the watershed is removed; therefore, the load is generally lower than existing conditions by over 90% overall, except for State Beach watershed which has a 57% reduction.

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

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Table VI-5. Build-out sub-embayment and surface water loads used for total nitrogen modeling of the Sengekontacket Pond System, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Farm Neck	10.926	3.337	-0.995
Majors Cove	13.003	1.189	5.821
Ocean Heights	19.962	5.932	-17.578
Trapps Pond	6.148	0.660	4.594
State Beach	0.115	-[1]	1.888

[1] Atmospheric deposition for State Beach is including within the atmospheric disposition for Ocean Heights

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of Sengekontacket Pond System was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most in Trapps Pond, with the water quality station at the inlet to Trapps Pond showing a 13.5% increase in total nitrogen. The stations in the main body of Sengekontacket Pond show only modest increases due to the efficient exchange of water with Nantucket Sound through the two inlets. Color contours of model output for the build-out scenario are present in Figure VI-7. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-4, which allows direct comparison of nitrogen concentrations between loading scenarios.

Table VI-6. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Sengekontacket Pond System. Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Farm Neck Inlet	Skt-1	0.308	0.310	+0.6%
Farm Neck Basin	Skt-2	0.320	0.324	+1.1%
Majors Cove	Skt-3	0.351	0.358	+2.2%
Majors Cove	**Skt-4**	**0.375**	**0.386**	**+2.8%**
Main Inlet	Skt-5	0.299	0.302	+0.9%
Ocean Heights	Skt-6	0.308	0.312	+1.3%
Ocean Heights	Skt-7	0.306	0.311	+1.8%
Ocean Heights	Skt-8	0.331	0.351	+6.1%
Trapps Pond	**Skt-9**	**0.382**	**0.434**	**+13.5%**

Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in Sengekontacket Pond System, for projected build-out loading conditions, and bathymetry. The approximate locations of the sentinel threshold stations for Sengekontacket Pond System (SKT-4 and SKT-9) are shown.

VI.2.6.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering each sub-embayment for the no anthropogenic load ("no load") scenario is shown in Table VI-7. The benthic flux input to each embayment was reduced (toward zero) based on the reduction in the watershed load (as discussed in §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 Sengekontacket Pond System, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Farm Neck	0.647	3.337	-0.597
Majors Cove	1.093	1.189	3.152
Ocean Heights	0.792	5.932	-10.423
Trapps Pond	0.238	0.660	1.977
State Beach	0.049	-[1]	1.198

[1] Atmospheric deposition for State Beach is including within the atmospheric disposition for Ocean Heights

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Again, total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) 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 ranging from 3% occurring near the northern inlet to Sengekontacket Pond within Farm Neck watershed to greater than 15% at the outlet from Trapps Pond. Results for each system are shown pictorially in Figure VI-8.

Table VI-8. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the Sengekontacket Pond System. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Farm Neck Inlet	Skt-1	0.308	0.298	-3.1%
Farm Neck Basin	Skt-2	0.320	0.302	-5.7%
Majors Cove	Skt-3	0.351	0.311	-11.2%
Majors Cove	**Skt-4**	**0.375**	**0.320**	**-14.7%**
Main Inlet	Skt-5	0.299	0.295	-1.5%
Ocean Heights	Skt-6	0.308	0.298	-3.5%
Ocean Heights	Skt-7	0.306	0.296	-3.2%
Ocean Heights	Skt-8	0.331	0.303	-8.3%
Trapps Pond	**Skt-9**	**0.382**	**0.324**	**-15.3%**

Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in Sengekontacket Pond System, for no anthropogenic loading conditions, and bathymetry. The approximate locations of the sentinel threshold stations for Sengekontacket Pond System (SKT-4 and SKT-9) are shown.

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 Sengekontacket Pond embayment system in the Towns of Oak Bluffs and Edgartown, MA, assessment is based upon data from the water quality monitoring baseline developed by the Martha's Vineyard Commission and the Towns and SMAST staff and our surveys of eelgrass distribution, benthic animal communities and sediment characteristics, as well as dissolved oxygen records conducted during the summer and fall of 2004. These data are integrated to form a multi-parameter assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for these systems (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen threshold determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll a (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). 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 autonomously recording dissolved oxygen sensors throughout Sengekontacket Pond at critical points in the system. The sensors were sited such that they would be representative of dissolved oxygen conditions within major sub-basins comprising the Sengekontacket Pond Estuary, namely Majors Cove, Trapps Pond and the main basin of Sengekontacket Pond (mid and south basins) The four dissolved oxygen moorings were deployed to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Sengekontacket Pond system was conducted for comparison to historic records by the Martha's Vineyard Commission and the 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 nutrient enrichment and 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. This is consistent with results from the Water Quality Monitoring Program indicating that phytoplankton production (blooms) within the basins of the Sengekontacket Pond Estuary is enhanced by nitrogen. This is based upon inorganic nitrogen to phosphorus ratios, where the system wide average is 5 and the maximum is 8. While this ratio approach (Redfield Ratio) is an approximation, where values <16 indicate nitrogen limitation, >16 phosphorus limitation, the low value of the ratio provides additional site-specific evidence that nitrogen is the appropriate nutrient for management of eutrophication in this system.

While temporal changes in eelgrass distribution provided a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet) in nutrient enrichment within much of the Sengekontacket Pond System, some areas have not historically or do not presently support eelgrass. In these areas, 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 4 mg L^{-1}, in open water estuarine environments. Massachusetts State Water Quality Classifications indicate that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Sengekontacket Pond system are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality. It is through the MEP and TMDL processes that management actions are developed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Sengekontacket Pond system (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. 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 Sengekontacket Pond system was collected during the summer of 2004.

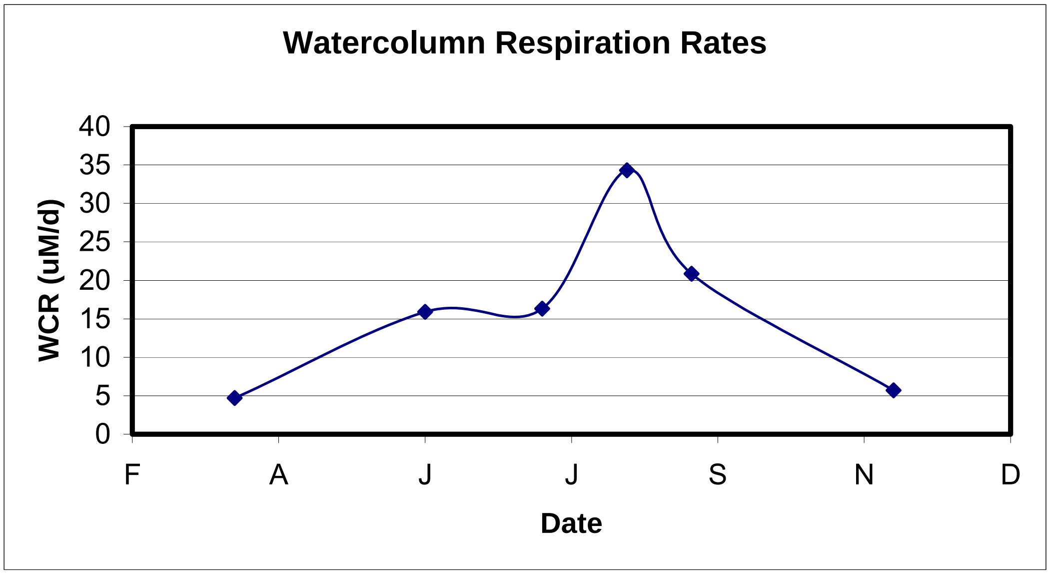

Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Sengekontacket Pond system evaluated in this assessment showed high frequency variation in watercolumn oxygen and chlorophyll levels, 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 48 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.

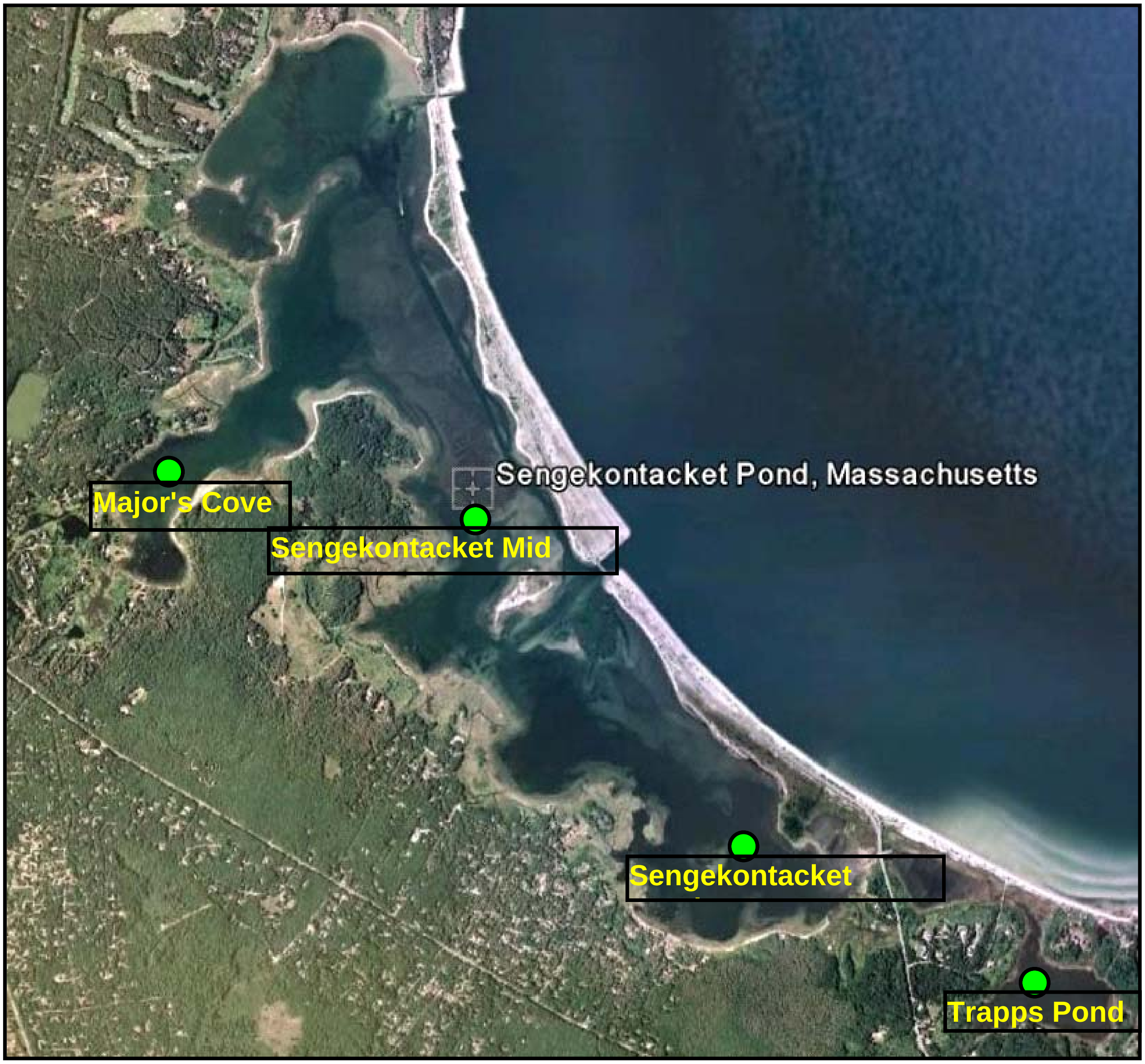

Figure VII-2. Aerial Photograph of the Sengekontacket Pond system in the Towns of Oak Bluffs and Edgartown showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2004. The Majors Cove mooring could not be recovered.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate moderately nutrient enriched waters within critical regions of the main basin of Sengekontacket as well as Trapps Pond (Figures VII-3 through VII-14). It should be noted that the Water Quality Monitoring Program observed similar levels of chlorophyll and bottom water oxygen depletion in Majors Cove as in the basins of Sengekontacket Pond. The oxygen data is consistent with a moderate level of organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll a. The measured levels of oxygen depletion and enhanced chlorophyll a levels follows the spatial pattern of total nitrogen levels in this system (Chapter VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

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

Station	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Sengenkontacket North	**8/13/2004**	**9/30/204**	**48.1**	**63%**	**15%**	**0%**	**0%**
			48.1	30.17	7.26	0.00	0.00
			Mean	1.12	0.25	N/A	N/A
			Min	0.03	0.03	0.00	0.00
			Max	8.86	0.68	0.00	0.00
			S.D.	1.64	0.18	N/A	N/A
Sengenkontacket South	**8/13/2004**	**9/30/204**	**48.1**	**55%**	**22%**	**3%**	**1%**
			48.1	26.49	10.71	1.60	0.43
			Mean	0.50	0.21	0.11	0.11
			Min	0.01	0.01	0.01	0.01
			Max	6.69	0.88	0.42	0.38
			S.D.	1.03	0.22	0.11	0.18
Trapp's Pond	**8/13/2004**	**9/30/204**	**48.1**	**29%**	**10%**	**4%**	**0%**
			48.1	14.07	4.67	2.01	0.00
			Mean	0.19	0.09	0.11	0.00
			Min	0.01	0.01	0.01	0.00
			Max	1.53	0.90	0.90	0.00
			S.D.	0.29	0.16	0.21	0.00

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

Station	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)
Sengenkontacket North	**8/13/2004**	**9/30/2004**	**47.9**	**48%**	**0.3%**	**0%**	**0%**	**0%**
Mean Chl Value = 5.2 ug/L			47.9	23.00	0.13	0.00	0.00	0.00
			Mean	0.42	0.06	N/A	N/A	N/A
			Min	0.04	0.04	0.00	0.00	0.00
			Max	2.21	0.08	0.00	0.00	0.00
			S.D.	0.43	0.03	N/A	N/A	N/A
Sengenkontacket South	**8/13/2004**	**9/30/2004**	**47.9**	**92%**	**0%**	**0%**	**0%**	**0%**
Mean Chl Value = 6.2 ug/L			47.9	44.29	0.00	0.00	0.00	0.00
			Mean	2.01	N/A	N/A	N/A	N/A
			Min	0.04	0.00	0.00	0.00	0.00
			Max	23.50	0.00	0.00	0.00	0.00
			S.D.	4.99	N/A	N/A	N/A	N/A
Trapps Pond	**8/13/2004**	**9/30/2004**	**47.9**	**70%**	**59%**	**9%**	**0%**	**0%**
Mean Chl Value = 10.9 ug/L			47.9	33.58	28.42	4.17	0.00	0.00
			Mean	0.99	0.69	0.13	N/A	N/A
			Min	0.04	0.08	0.04	0.00	0.00
			Max	2.83	0.92	0.33	0.00	0.00
			S.D.	0.58	0.16	0.10	N/A	N/A

The oxygen records show that the inner sub-embayments of Sengekontacket South and Trapps Pond, which receive significant watershed nitrogen loads and have lower flushing rates, have the largest daily oxygen excursions, a nutrient related response. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration indicates that the inner tidal reaches of the Sengekontacket system are nitrogen enriched.

Measured dissolved oxygen depletion indicates that regions of Sengekontacket Pond, such as the southern area and to a greater extent, Trapps Pond, show moderate levels of oxygen stress, as does bottom water oxygen data from the monitoring program (2003-07) for upper Majors Cove. The largest oxygen depletions and excursions were observed in Trapps Pond. The observed spatial pattern indicated that the level of oxygen depletion (Table VII-1) and chlorophyll a (Table VII-2) and total nitrogen levels increased with increasing distance from the tidal inlet and into the smaller sub-embayment of Trapps Pond. The Water Quality Monitoring Program, while not yielding insight into the short-term temporal variation in oxygen and chlorophyll, does yield a good baseline for looking at the spatial distribution. The results support the mooring data, also indicating moderate levels of nitrogen enrichment in Trapps Pond (outflow) and upper Majors Cove with only a low level of enrichment in the main basin of Sengekontacket Pond. Measured bottom water oxygen depletion followed this same pattern as did the gradient in chlorophyll. There was a slight but discernable difference within the main basin of the Pond with the South basin, adjacent Ocean Heights, having slightly lower nutrient related water quality than the mid basin.

The pattern of oxygen depletion, elevated chlorophyll a and nitrogen levels are consistent with the observed pattern of eelgrass loss (Section VII.3) and quality of infaunal habitats (Section VII.4) and are indicative of an estuarine system that is beyond its ability to assimilate nitrogen loads without impairment. The embayment specific results are as follows:

Major's Cove:

The Major's Cove mooring was centrally located within the upper reach of Major's Cove. Unfortunately, the data collected by the mooring could not be obtained as the meter could not be located and retrieved. It is assumed that the mooring was stolen and vandalized. As a result, oxygen and chlorophyll a related water quality assessment is based upon the Water Quality Monitoring Program baseline collected summers, 2003 - 2009.

Only modest oxygen depletion was observed over the 25 sampling events. Oxygen levels were always > 4 mg L^{-1} and <5 mg L^{-1} 28% of events. This level of oxygen depletion paralleled the chlorophyll a levels which averaged 4.9 ug L^{-1}, with a maximum of 12.5 ug L^{-1} over the study period. The magnitude of oxygen depletion and chlorophyll levels are consistent with the moderate level of nitrogen enrichment (tidally averaged TN of 0.375 mg N L^{-1}, Chapter VI). However, the water quality parameters suggest organic enrichment and a moderate level of habitat impairment relative to eelgrass.

Sengekontacket Mid Basin (Figures VII-3 and VII-4):

The Sengekontacket mid basin mooring site was centrally located within the main basin between the two inlets but closer to the southern inlet through which most of the tidal exchange with Vineyard/Nantucket Sound occurs (Figure VII-2). Daily excursions in oxygen levels at this location were moderate, generally varying only 2 mg L-1 and not indicative of significant organic matter enriched conditions. Oxygen varied primarily with light (diurnal cycle) and the tides. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed when low tide occurred at the end of the photocycle (ca. 1500 hrs).

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 63% and 15% of the 48 day record, although oxygen was always >4 mg L^{-1}, similar to Major's Cove (Table VII-1). The frequent but moderate oxygen declines were consistent with the moderate levels of phytoplankton biomass as measured by chlorophyll a. Chlorophyll a averaged 5.2 ug L-1 over the record and only approached 10 ug L-1 in a single event. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality, a level double the average chlorophyll a observed in this basin by the mooring or the Water Quality Monitoring Program (3.3 ug L-1). These levels of chlorophyll are indicative of an open water basin with only moderate nitrogen and organic matter enrichment (Table VII-2, Figure VII-4). .

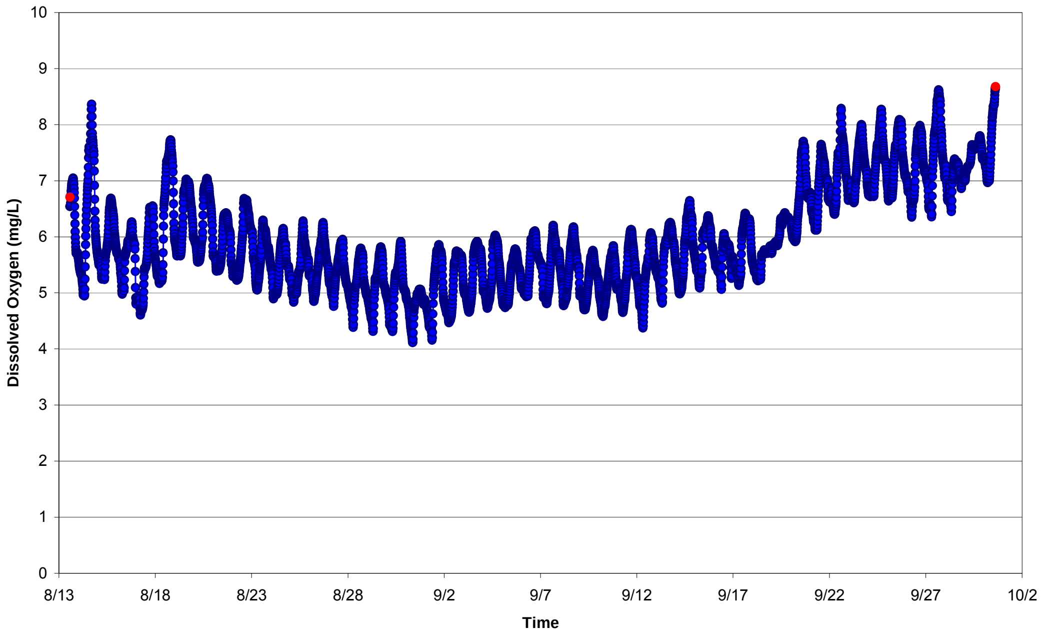

Figure VII-3. Bottom water record of dissolved oxygen at the Sengekontacket mid basin station, Summer 2004 (location in Figure VII-2). Calibration samples represented as red dots.

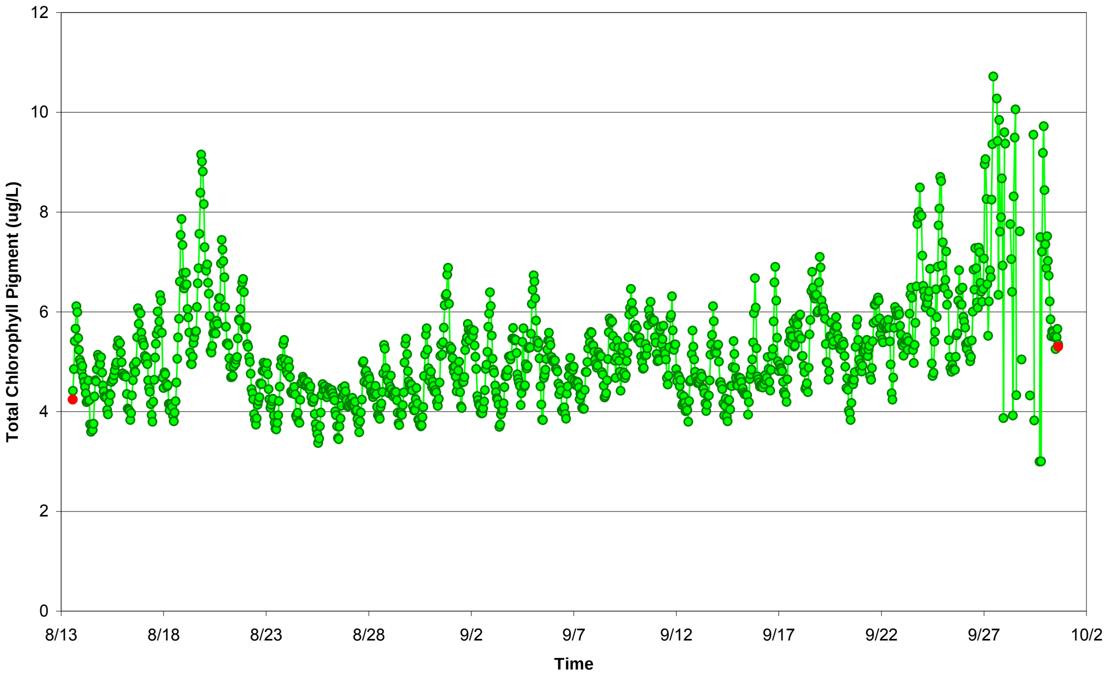

Figure VII-4. Bottom water record of Chlorophyll-*a* in the Sengekontacket mid basin station, Summer 2004. Calibration samples represented as red dots.

Sengekontacket South (Figures VII-5 and VII-6):

The Sengekontacket Pond southern basin mooring was centrally located within the main basin of Sengekontacket Pond at the southern end approximately 1.1 km from the main inlet through which high quality waters enter the basin from Vineyard Sound on each flooding tide (Figure VII-2). Daily excursions in oxygen levels at this location were more pronounced than at the Sengekontacket mid basin mooring location, generally on the order of 4 mg L^{-1} over a single diurnal cycle. While oxygen levels in excess of air equilibration occurred they were typically small and infrequent. Oxygen varied primarily with light (diurnal cycle) and the tides. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed when low tide occurred at the end of the photocycle (ca. 1500 hrs).

Oxygen levels were <6 mg L^{-1} over half the time but infrequently dropped below 5 mg L^{-1} (10% or record) and rarely declined to <4 mg L^{-1} (3% of record; Table VII-1). The observed moderate level of oxygen depletion and observed limited magnitude of high oxygen (excess of air equilibration) suggests a system moderately nitrogen and organic matter enriched. Consistent with these observations, chlorophyll a was only moderately elevated averaging 6.2 ug L^{-1} over the 48 day record and rarely exceeding 9 ug L^{-1}. Chlorophyll was relatively constant without a cycle of major blooms (Table VII-2, Figure VII-4). Similarly, the Water Quality Monitoring baseline shows similar chlorophyll levels averaging 5.3 ug L^{-1}, with a maximum of 13.6 ug L^{-1} (station Skt-8, nearest the mooring site). The observed levels of oxygen depletion and chlorophyll a are consistent with the observed TN levels (tidally averaged, 0.306-0.331 mg N L^{-1}).

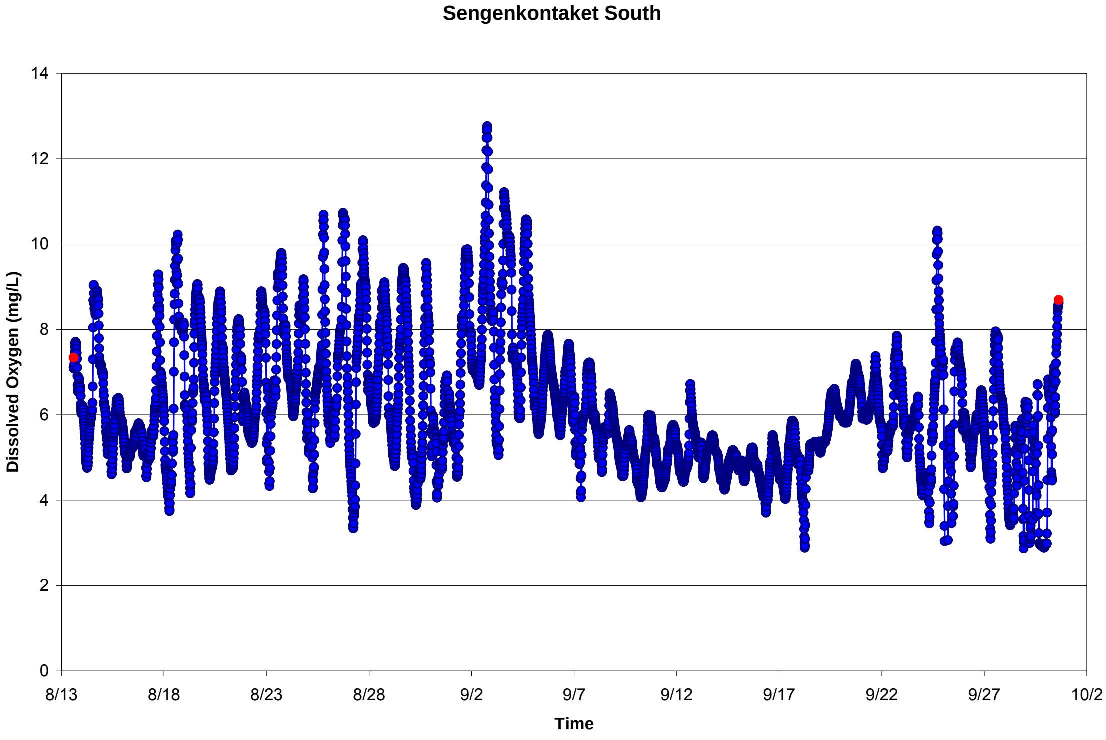

Figure VII-5. Bottom water record of dissolved oxygen at the Sengekontacket Pond south basin, Summer 2004 (location in Figure VII-2). Calibration samples represented as red dots.

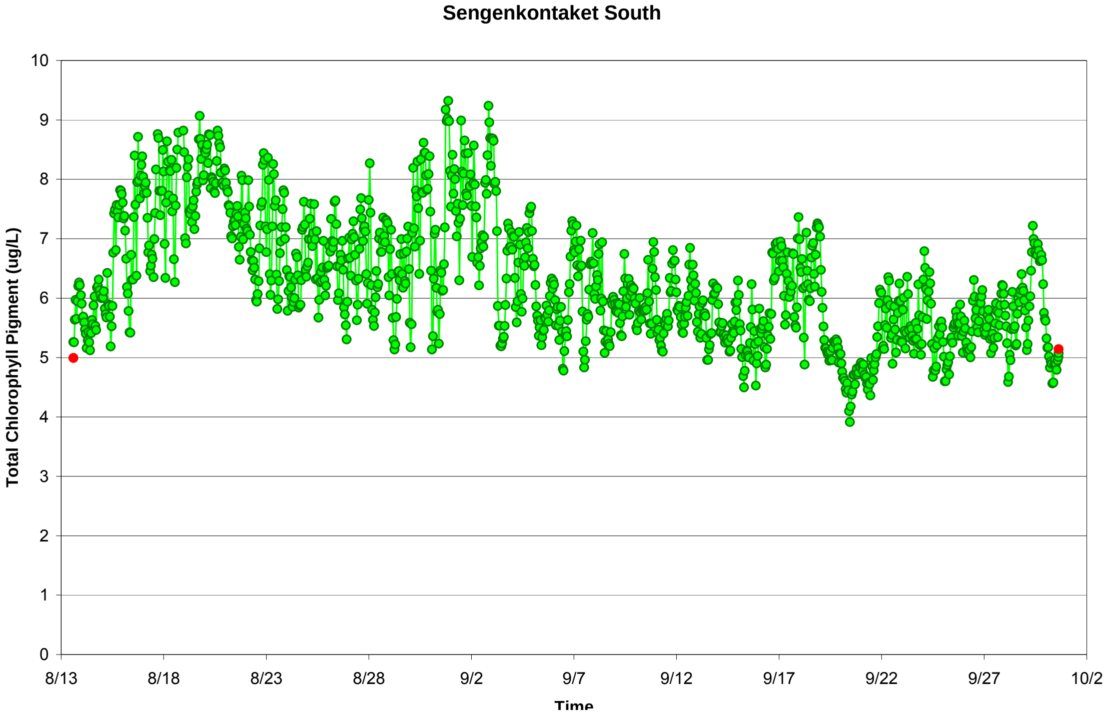

Figure VII-6. Bottom water record of Chlorophyll-*a* in the Sengekontacket South station, Summer 2004. Calibration samples represented as red dots.

Trapps Pond (Figures VII-7 and VII-8)

The Trapps Pond mooring was situated within the upper basin which supports the major eelgrass beds within this tributary sub-embayment to Sengekontacket Pond. Trapps Pond is significantly tidally restricted, increasing the sensitivity of this basin to nitrogen loading. As a sub-embayment, Trapps Pond exchanges tidal waters with the southern basin of Sengekontacket Pond rather than directly with Vineyard Sound. This tributary sub-embayment is composed of two basins, an inner basin in which the DO / CHLA mooring was placed and an outer basin that support the outlet to Sengekontacket Pond. Despite its enclosed tidally restricted conditions, bottom water oxygen in Trapps Pond is generally >6 mg L^{-1} (71% of record) and infrequently declines to < 5 mg L^{-1} and rarely to ~4 mg L^{-1} (Figure VII-11, Table VII-1). Similarly, large daily excursions in oxygen levels were not observed in the Trapps Pond oxygen record. These moderate depletions are consistent with the moderate chlorophyll levels, which averaged 10.9 ug L^{-1} but rarely exceeded 18 ug L^{-1} over the 48 day record.

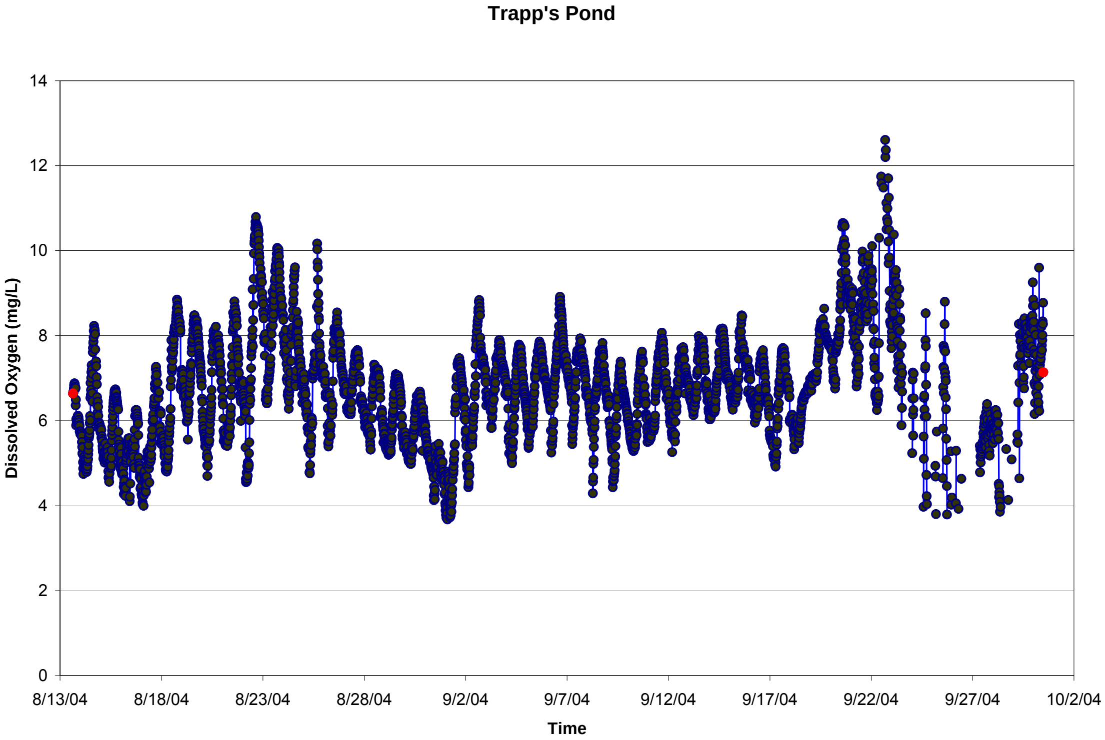

Figure VII-7. Bottom water record of dissolved oxygen at the Trapp's Pond station, Summer 2004 (location in Figure VII-2). Calibration samples represented as red dots.

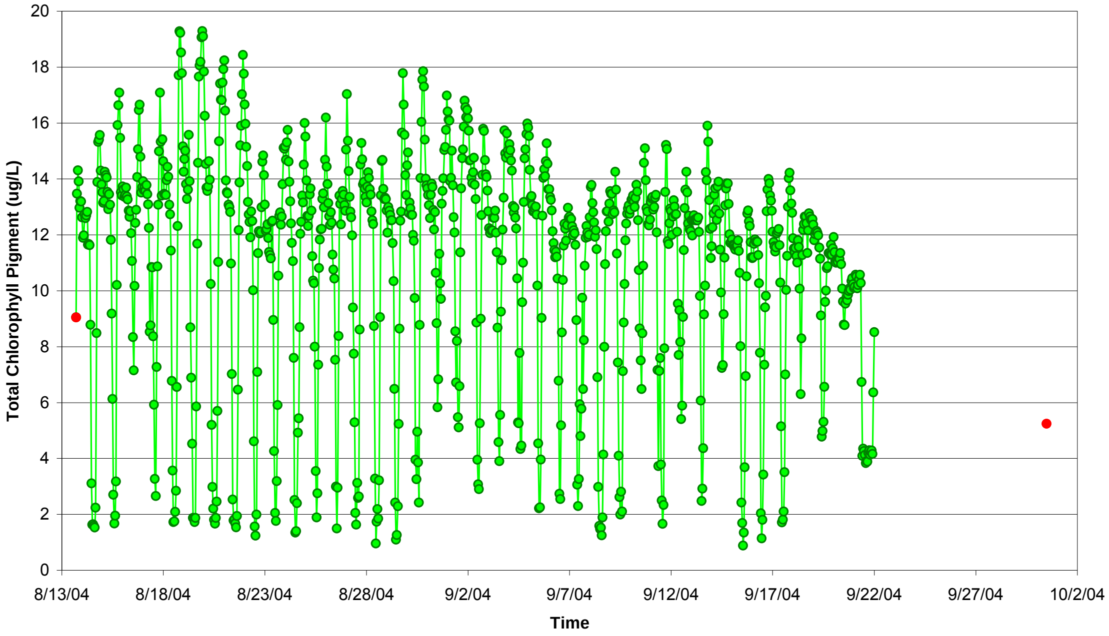

Figure VII-8. Bottom water record of Chlorophyll-*a* in the Trapp's Pond station, Summer 2004. Calibration samples represented as red dots.

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data was conducted for the Sengekontacket Pond Embayment System by the Martha's Vineyard Commission and the MassDEP Eelgrass Mapping Program as part of the MEP. Surveys were conducted in 1998 and 2006, as part of this effort. Additional analysis of available aerial photos from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. The 1951 data were only anecdotally validated, while the 1998 and 2006 maps were field validated. Additionally, qualitative records brought forward by the Duke's County Fisherman's Association were used to further clarify the presence/absence of eelgrass in specific areas of Sengekontacket Pond. The primary use of the data is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1998 to 2006 (Figure VII-9 to Figure VII-11); 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.

At present, eelgrass exists only within a small portion of the system at the upper reaches of Major's Cove and in the inner and outer basins of Trapps Pond. Based on the 1998 and 2006 eelgrass surveys and the 2004 diver surveys as part of the MEP, the remaining eelgrass bed in Majors Cove appears to be limited to a small area contained within a small cove at the uppermost reach of this basin. Eelgrass habitat in Trapps Pond is primarily in the upper basin with patches distributed in the lower basin. However, the eelgrass in Trapps Pond was observed to be heavy with epiphytes and the sediments are very soft with a thin benthic algal mat, indicative of nitrogen enriched conditions and an impaired habitat.

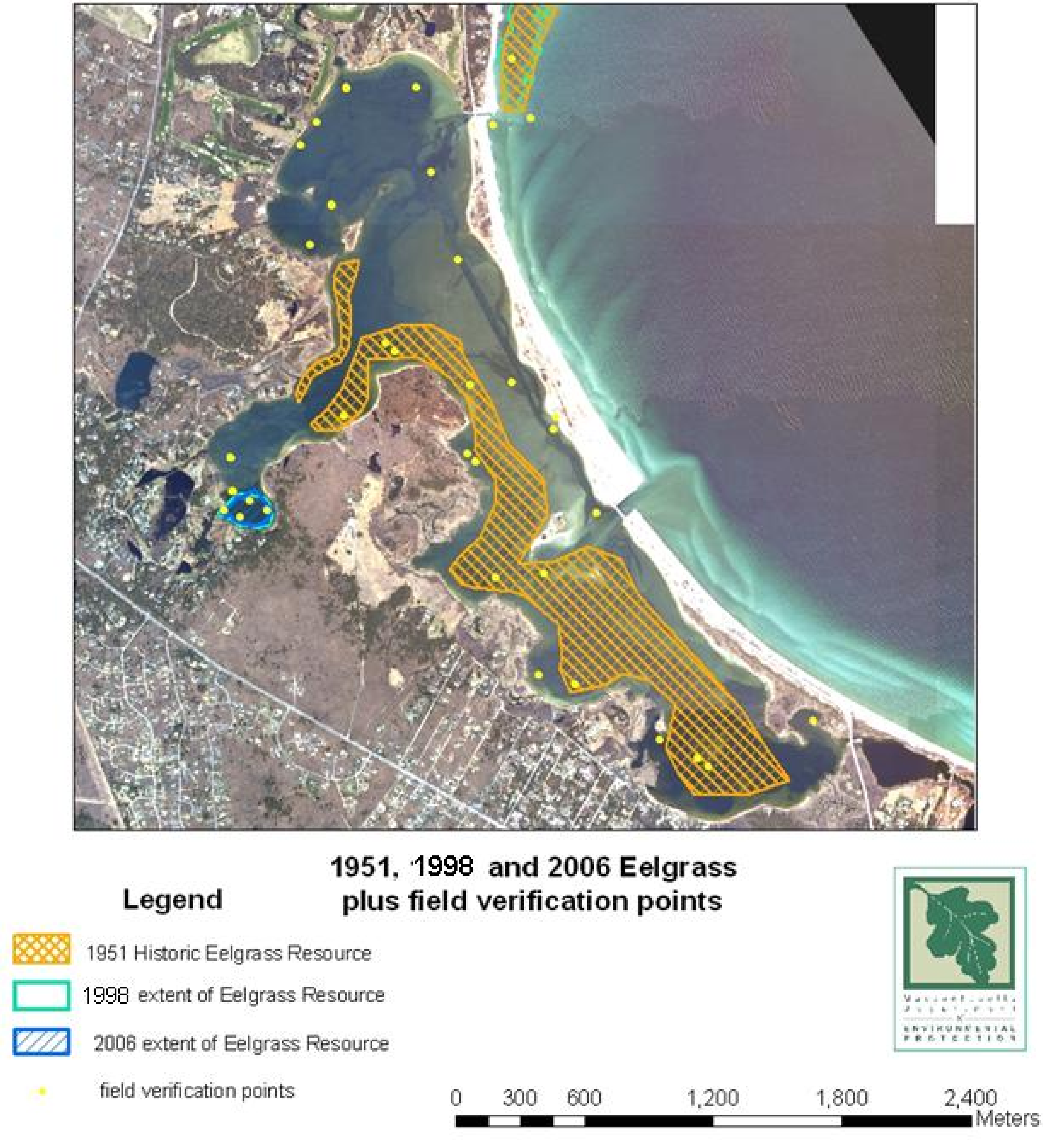

Figure VII-9. Eelgrass bed distribution within the Sengekontacket Pond System. The MVC's 1998 coverage is depicted by the green outline inside of which circumscribes the eelgrass beds. The blue (2006) areas were mapped by DEP. The 1951 baseline coverage is outlined in gold. All data was provided by the MassDEP Eelgrass Mapping Program.

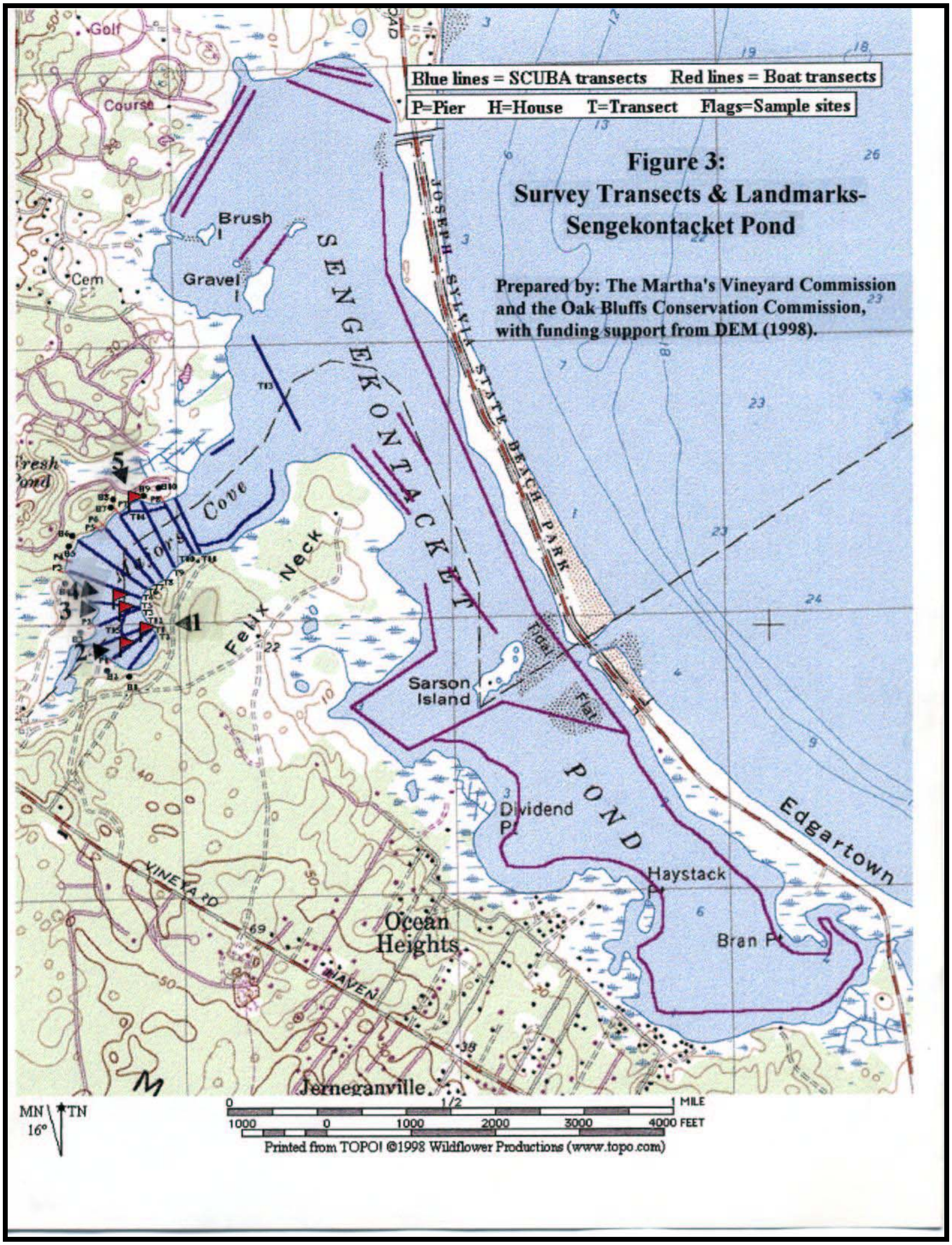

Figure VII-10. Eelgrass survey areas in Sengekontacket Pond and Trapps Pond as conducted by the Martha's Vineyard Commission in 1998

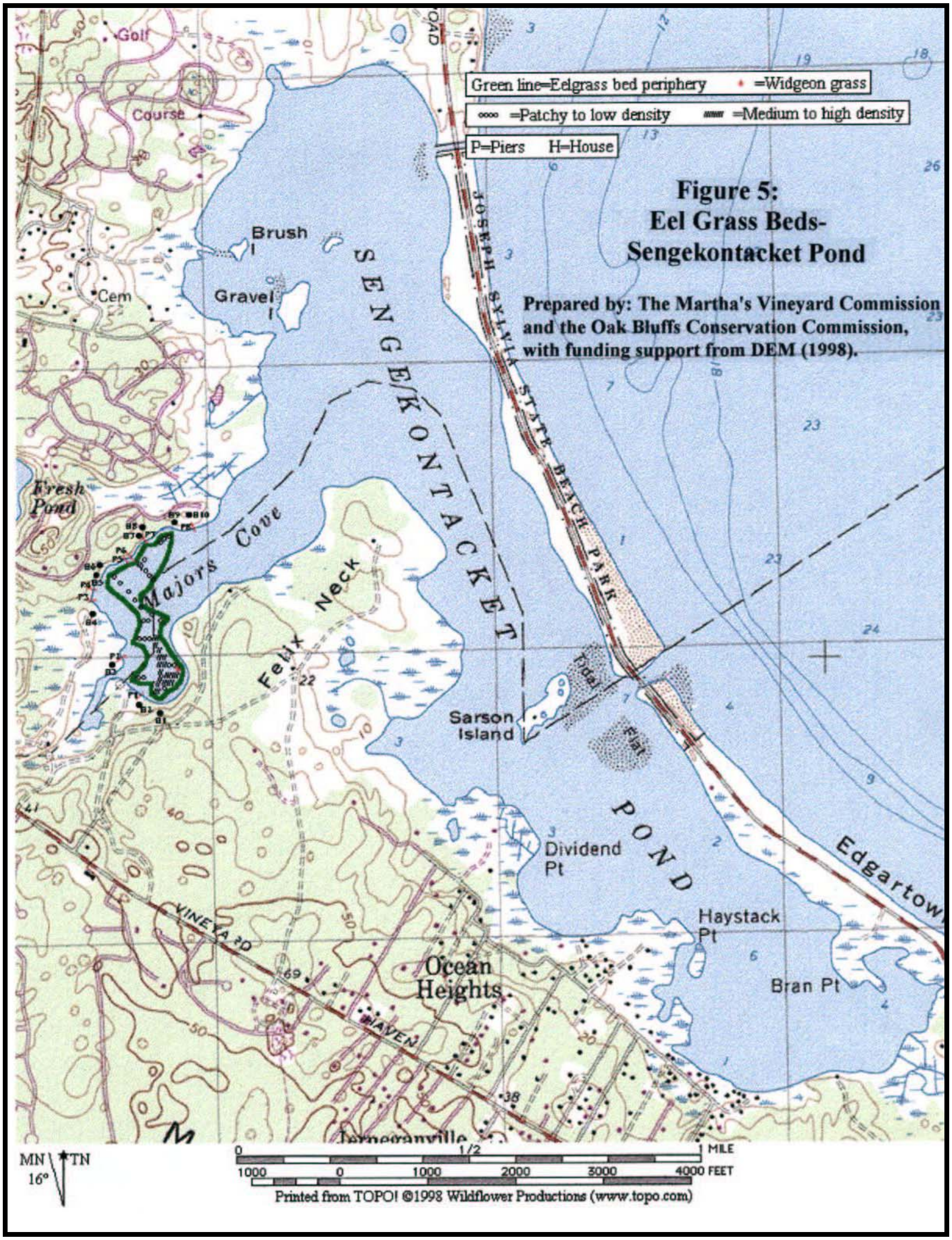

Figure VII-11. Map of eelgrass coverage in Sengekontacket Pond and Majors Cove as completed by the Martha's Vineyard Commission in 1998

The lower 1/2 of the Majors Cove sub-embayment and most of the main basin of Sengekontacket Pond from Majors Cove to Trapps Pond supported eelgrass in 1951, according to the MassDEP Eelgrass Mapping Program analysis. The results of the 1998 and 2006 MVC and MassDEP surveys have been confirmed by multiple MEP staff conducting infaunal animal and sediment sampling and mooring studies. However, between the 1951 and 1998 surveys, the extensive eelgrass coverage of the lower reach of Majors Cove and the mid and southern basins of Sengekontacket Pond had been lost. Eelgrass habitat is currently not present in these areas, persisting only in the upper reach of Majors Cove as patches and in Trapps Pond. It should be noted that even though there is no quantitative evidence that the northern most portion of Sengekontacket Pond had eelgrass in the recent past that should not lead managers to believe that this area has become impaired for this resource. This statement is supported by anecdotal evidence provided by members of the Dukes County Fisherman's Association which indicated in a qualitative manner that eelgrass was observed in the northern portion of the main basin of Sengekontacket Pond as far back as in the 1970's and 1980's.

The 1998 MVC survey of Trapps Pond covered both the inner and outer basins, approximately 45 acres in area compared to the 716 acre area of Sengekontacket Pond. Trapps Pond exchanges water with Sengekontacket Pond via a culvert beneath the State Highway. The culvert is presently restricting tidal flows and flushing of Trapps Pond. Trapps Pond is shallow, with the depth of water throughout both basins 1.0-1.5 meters or less. Eelgrass beds were observed in both basins (Figure VII-12). The bed in the outer basin was characterized by patches of eelgrass on the order of 1 to 2 meters diameter. The northern portion of the inner basin did not support eelgrass. In the inner basin, the eelgrass bed was continuous throughout, beginning at water depths of about 2 feet and 10 to 25 meters from shore. The eelgrass blades were observed to be heavily coated with epiphytes and epibionts including algae as well as colonial tunicates and worm tubes.

The current decline of eelgrass beds relative to historical distributions is expected given the moderate depth of these basins and the periodic oxygen declines and presence of significant drift algae in these sub-basins. Although indictors generally show only moderate levels of nutrient enrichment, moderate oxygen declines and moderately high chlorophyll level, the depth of the basins also plays a role. The observed loss of eelgrass is consistent with the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion. As a result of the significant loss of eelgrass habitat in this system, it is clear that management of the Sengekontacket Pond Embayment System must focus on nitrogen management for restoration of these resources rather than protection.

Other factors which influence eelgrass bed loss in embayments can also be at play in the Sengekontacket Pond Embayment System, though the recent loss appears completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density as the system does not support any permanent boat mooring area and only has a few scattered moorings. While pier construction can cause impacts to eelgrass beds, there are very few piers on the shores of Sengekontacket Pond. On the other hand, boating pressure may be adding additional stress in nutrient enriched areas, but it does not seem to be the overarching factor, especially given structure of these basins and the limited access and navigable water. Shell fishing activities such as scallop dredging and (historic) water jetting for clams can also be factors affecting eel bed loss, however, given the other ecological indicators quantified by the MEP Technical Team (D.O., CHLA, infauna), eelgrass loss in Sengekontacket Pond does appear consistent with nutrient enrichment.

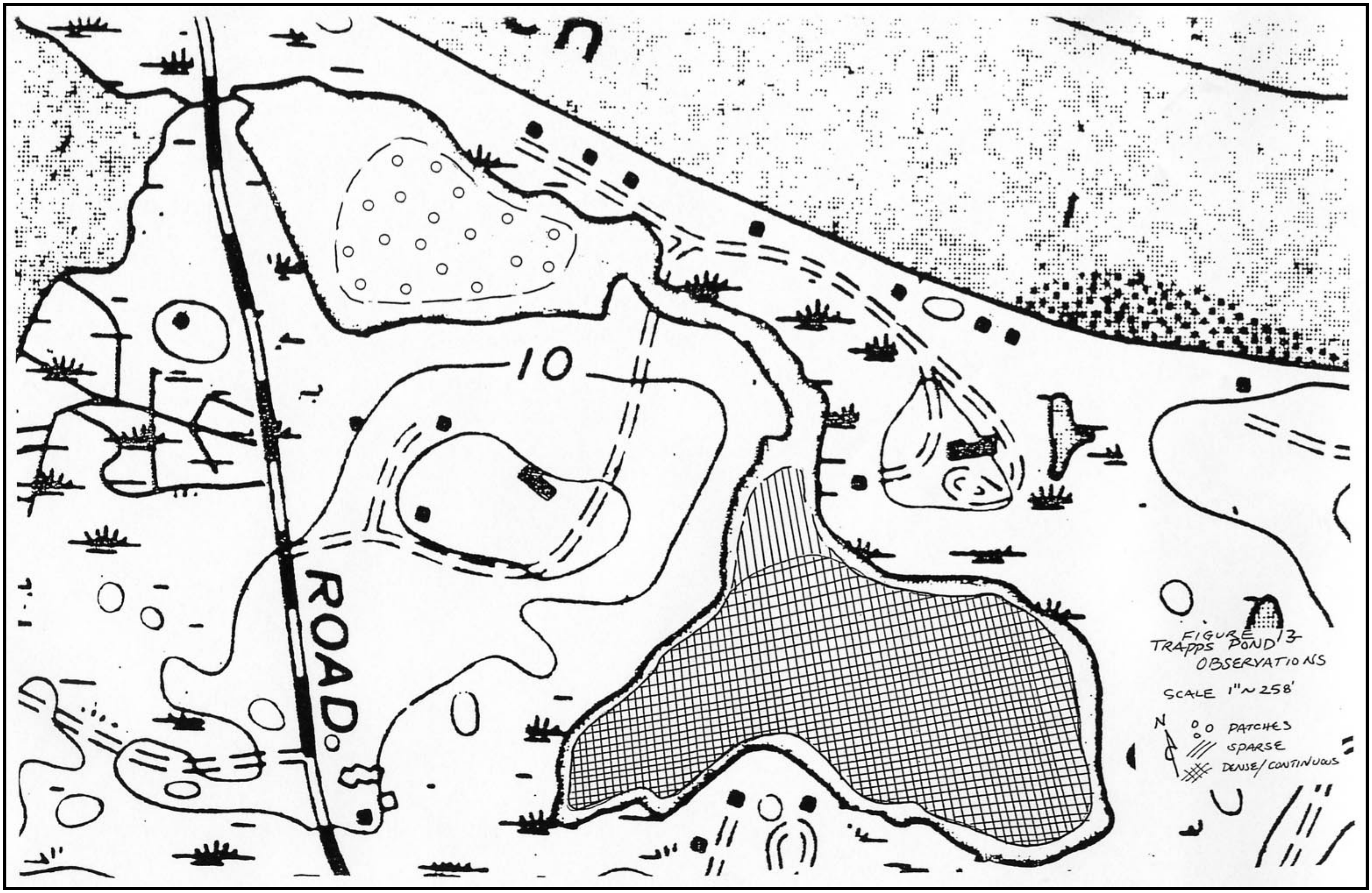

Figure VII-12. Eelgrass distribution in Trapp's Pond as developed by the MVC in 1997-98 field survey.

It is possible to determine quantitative short- and long-term rates of change in eelgrass coverage from the mapping data of Sengekontacket Pond and Majors Cove. Unfortunately, there is insufficient temporal data on Trapps Pond for this type of analysis. Sengekontacket Pond and Majors Cove eelgrass areas from the 1951, 1998 and 2006 maps indicate that a minimum eelgrass bed area that might be recovered (on the order of 200 acres) if nitrogen management alternatives were implemented (Table VII-3). It is possible that a greater area of eelgrass habitat could be restored, as the 1951 coverage is likely an underestimate as a result of mapping limitations. Note that restoration of this eelgrass habitat will necessarily result in restoration of other resources throughout the Sengekontacket Pond Embayment System, specifically the shallower eelgrass habitat in the main basin of the lagoon. Also, nitrogen management will lower nitrogen enrichment of Trapps Pond, either directly through management of nitrogen sources within the Trapps Pond watershed or through lower nitrogen concentrations in inflowing tidal water from Sengekontacket Pond. One clear management alternative for restoring the moderate impairment of Trapps Pond habitats, that needs to be evaluated, is to reduce the tidal restriction currently caused by the undersized culvert. Reducing the restriction will increase tidal exchange with the lower nitrogen waters of Sengekontacket Pond and lower the nitrogen levels in Trapps Pond waters. While it appears that much of the Sengekontacket Embayment System is presently supporting impaired eelgrass habitat, benthic animal habitat is also a critical estuarine resource which generally has a higher tolerance for nitrogen enrichment than eelgrass. Infauna habitat quality is evaluated in the section below.

Table VII-3. Changes in eelgrass coverage in the Sengekontacket Pond Embayment System within the Towns of Oak Bluffs and Edgartown over the past half century (MassDEP, C. Costello). It appears that more than 200 acres of eelgrass habitat can be regained through nitrogen management of this system and its watershed.

Sengekontacket Pond Embayment System: Temporal Change in Eelgrass Coverage			
1951 acreage	**1998 acreage**	**2006 acreage**	**% Loss 1951 - 2006**
219.9	**7.0**	**5.5**	**97%**

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling for benthic community characterization was conducted at 19 locations throughout the Sengekontacket Pond Embayment System (Figure VII-13) with three of those sampling sites being located in Trapps Pond. At each site 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, given the significant loss of eelgrass beds, the Sengekontacket Pond System is clearly impaired by nutrient overloading. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

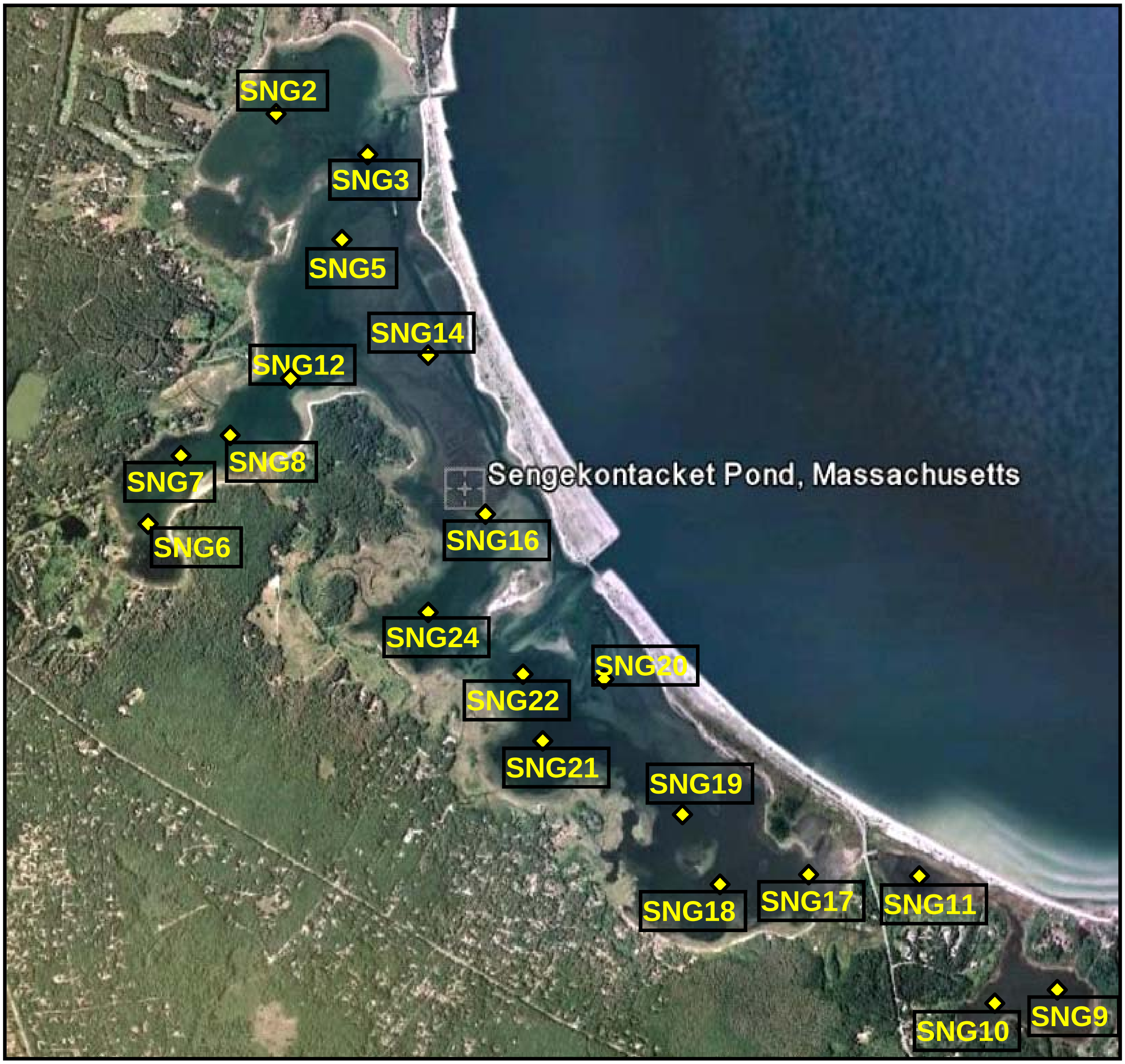

Figure VII-13. Aerial photograph of the Sengekontacket Pond system showing location of benthic infaunal sampling stations (blue symbol).

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

Overall, the Infauna Survey indicated that most areas within the main Sengekontacket Pond basin are supporting high to moderate quality infaunal habitat, with moderate to high numbers of species and individuals (Table VII-4). The highest quality habitat was found within the middle section of Sengekontacket Pond, which is adjacent the main tidal inlet. The mid basins had infaunal communities with high numbers of species (25), moderate to high numbers of individuals (309), high diversity (3.31) and Evenness. The community contains mollusks and crustaceans, in addition to the complement of polychaetes, including some deep burrowers. The northern reach of the main Sengekontacket Pond basin (Farm Neck basin) supports a different community, still with some crustaceans and mollusks, but with some organic enrichment tolerant species (e.g. Capitellids, Spionids and Tubificids) dominating some samples. The community is productive with high numbers of species and individuals, with moderate to high diversity and Evenness, consistent with its generally low level of nitrogen (tidally averaged TN, 0.32 mg N L^{-1}). While the prevalence of organic enrichment species indicates impairment, the numbers of species and individuals and high diversity suggests that impairment is low. Majors Cove showed a gradient from the upper to lower tidal reach, with more crustaceans and mollusks in the upper than lower reach. Overall, the basin presently supports moderate numbers of individuals across a moderate to high number of species with high diversity and evenness. The sediments are generally soft mud with a thin oxidized surface and without significant accumulation of drift algae. It appears that the benthic habitat currently is of high to moderate quality. In contrast, the southern basin within the main basin of Sengekontacket Pond appears to be supporting variable benthic animal habitat with higher quality near the inlet and lower quality on the inland side. The infauna community at sites near the inflow tidal inlet (SNG-22, 24) indicate very high quality habitat, with high numbers of species, high diversity and Evenness, and moderate numbers of individuals. The community has high numbers of mollusks, and some deep burrowing forms. In contrast, away from the inlet channel, there are fewer species and moderate diversity and Evenness. The community is productive with high numbers of individuals, and limited numbers of organic enrichment species. It is likely that the widely distributed drift algae accumulations are negatively affecting this community. The tidally restricted basins of Trapps Pond, which still supports eelgrass habitat, have productive benthic animal communities with high numbers of individuals, but low species numbers, diversity and Evenness. However, the communities are dominated by amphipods (*ampelisca, leptotheirus*: 66% of community) indicative of the organic enrichment and elevated chlorophyll a and nitrogen in this basin. Amphipods are indicative of a transitional environment and were among the first groups to colonized the sediments of Boston Harbor as it recovered. These invertebrates are tolerant of moderate levels of organic matter enrichment and oxygen depletion.

The infaunal habitat quality in Sengekontacket Pond and Trapps Pond was consistent with the data collected on levels of dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in each component of the system. Classification of habitat quality necessarily included the structure of the specific estuarine basin. Based upon this analysis it is clear that the tributary sub-embayment basin of Trapps Pond is presently supporting moderately impaired benthic habitat, while the northern and middle regions and the area near the tidal inlet are supporting high quality habitat. Similarly, Majors Cove has benthic animal communities indicating a range from high quality to slightly impaired habitat quality. In contrast, the southern basin of Sengekontacket Pond, south of the main tidal inlet, has spatially variable (patchy) infaunal animal communities. The community contains significant numbers of crustaceans and mollusks with some deep burrowers, but the numbers of individuals and species indicates impairment. Given the patchiness of the habitat, it appears to be being negatively affected by the large amount of drift algae present in summer throughout this southern basin. In general, it appears that the habitat quality within these basins, as manifested by the changes in eelgrass coverage and benthic community characteristics, is consistent with the observed nitrogen and organic matter enrichment and level of oxygen depletion, as well as the sediment characteristics and macroalgal abundance and distribution.

Table VII-4. Benthic infaunal community data for the Sengekontacket Pond Embayment System. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m2). Stations refer to map in figure VII-13, replicate samples were collected at each location. S.E. is the standard error of the mean; N is the number of samples.

	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Farm Neck Basin (Stations 2,3,5)					
Mean	**19**	**281**	**14**	**2.76**	**0.65**
S.E.	**2**	**107**	**3**	**0.31**	**0.05**
N	**4**	**4**	**4**	**4**	**4**
Mid Main Basin (Stations 14,16, 24)					
Mean	**25**	**309**	**17**	**3.31**	**0.71**
S.E.	**1**	**84**	**2**	**0.23**	**0.04**
N	**5**	**5**	**5**	**5**	**5**
Ocean Heights Basin (Stations 17,18,19,20,21,22)					
Mean	**14**	**252**	**11**	**2.89**	**0.80**
S.E.	**2**	**77**	**2**	**0.22**	**0.03**
N	**9**	**9**	**8**	**9**	**9**
Majors Cove Basin (Stations 6,7,8,12)					
Mean	**17**	**110**	**15**	**3.30**	**0.82**
S.E.	**1**	**15**	**1**	**0.08**	**0.03**
N	**7**	**7**	**4**	**7**	**7**
Trapps Pond Basin (Stations 9,10,11)					
Mean	**11**	**893**	**8**	**1.85**	**0.54**
S.E.	**1**	**482**	**1**	**0.71**	**0.21**
N	**6**	**6**	**6**	**6**	**6**

The results of the Infauna Survey indicate that the nitrogen management threshold analysis (Chapter VIII) targeting restoration of eelgrass habitat needs to also aim for lowering nitrogen enrichment for restoration in those basins with moderately impaired benthic habitat. However, it is important to note that in general the Sengekontacket Pond Embayment System is supportive of high quality infauna habitat and that impairment of this critical habitat to the extent that it was found, is moderate. It is clear that the habitat impairments within the Sengekontacket Pond Embayment System are associated with nitrogen enrichment. The loss of the extensive historical eelgrass makes restoration of this resource the primary focus for nitrogen management. Secondarily, the sub-basins that have slightly impaired benthic habitat should be restored as a consequence of management to restore the eelgrass habitat. Restoring these habitats should be the focus of the nitrogen management threshold analysis (Chapter VIII).

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth and available to the MEP Technical Team. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the propagation of shellfish. As is the case with many systems on Cape Cod, the majority of the enclosed waters of the Sengekontacket Pond system is conditionally approved for the taking of shellfish during specific times during the year, typically the cold winter months, indicating the system is generally supportive of shellfish communities. However, in the upper most reaches of the system, specifically Majors Cove and Trapps Pond, harvest of shellfish is prohibited year round indicating the presence of a persistent environmental contaminant. In the case of Majors Cove closure, that is potentially due to bacterial contamination from avian wildlife and/or failing septic systems in the Majors Cove sub-watershed (though no specific evidence was found indicating that septic systems are the source for bacterial contamination in the pond). The closure of Trapps Pond is likely due to bacterial contamination from wetland surfaces and natural fauna living on or around Trapps Pond. The major shellfish species with potential habitat within the Sengekontacket Pond Estuary are mainly quahogs (*Mercenaria*) and bay scallops extending all the way up to Majors Cove (Figure VII-14) as well as soft shelled clams (*Mya arenaria*) in shallower waters. In addition, if habitat conditions improve there is also the potential for small grow areas of bay scallops to develop, mostly in the shallow near shore waters along the fringe of Sengekontacket Pond.

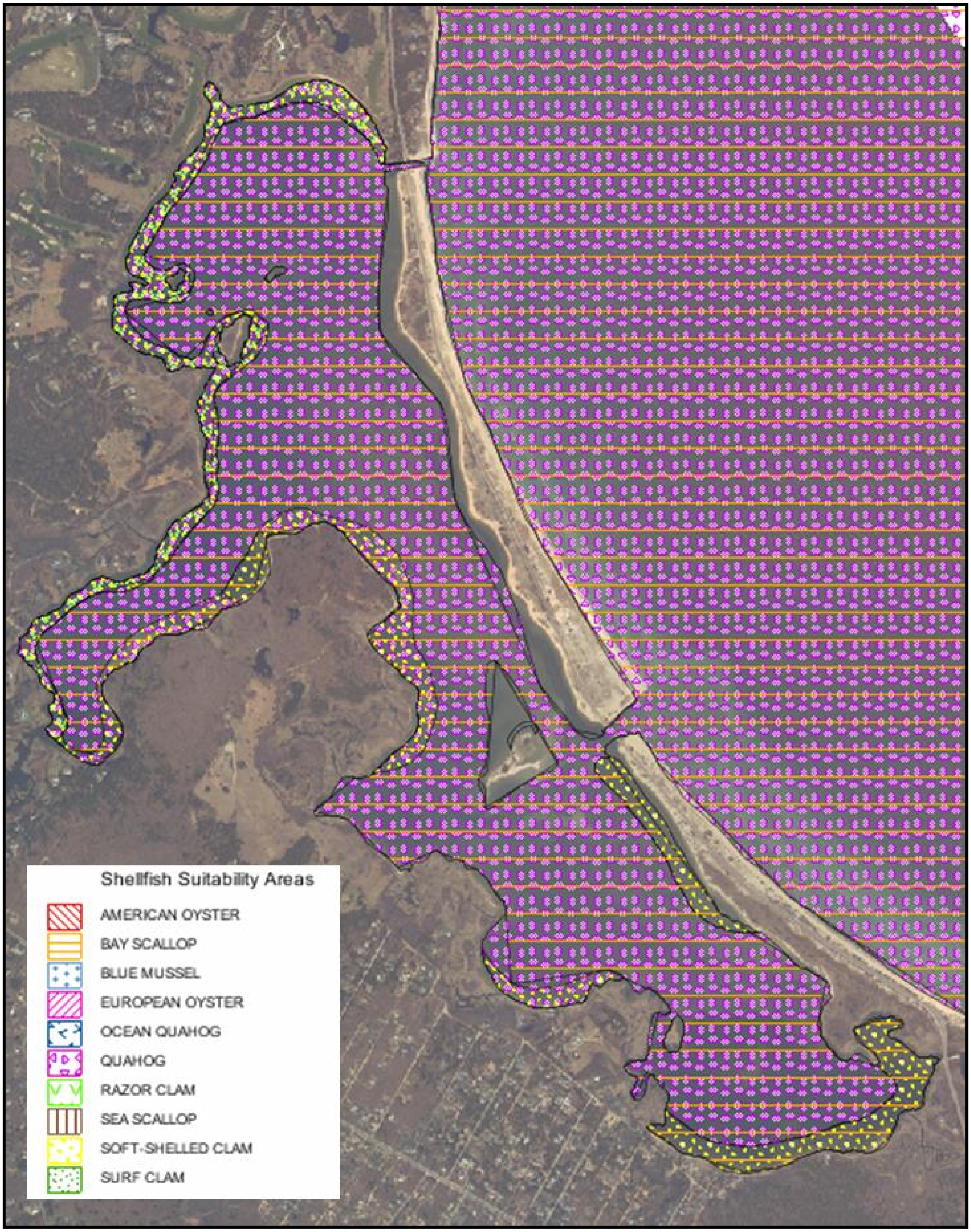

Figure VII-14. Location of shellfish suitability areas within the Sengekontacket Pond Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll). Additional information on temporal changes within each sub-embayment of an estuary, its associated watershed nitrogen load and geomorphological considerations of basin depth, stratification and functional type further strengthen the analysis. These data were collected to support threshold development for the Sengekontacket Pond Embayment System by the MEP and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline Water Quality Monitoring Program conducted by the Martha's Vineyard Commission and the Towns of Oak Bluffs and Edgartown, with technical and analytical support from the Coastal Systems Program at SMAST-UMass Dartmouth.

The Sengekontacket Pond Embayment System is a complex estuary formed as a composite of drowning a valley (upper reaches) and the development of a coastal lagoon formed as a barrier beach developed, separating the estuary from the adjacent open waters of Vineyard Sound. The main basins are moderate in depth, except for the shallow tidally restricted basin of Trapps Pond. While there is fringing salt marsh throughout Sengekontacket Pond Embayment System, the basins are functioning as typical embayment systems. Each component of a specific functional type (salt marsh basin, embayment, tidal river, deep basin (sometimes drown kettles), shallow basin, etc.) having a different natural sensitivity to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of the specific type of basin and the ability to support eelgrass beds and the types of infaunal communities that they support. At present, the Sengekontacket Pond Estuary is showing low to moderate nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Table VIII-1), indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

The measured levels of oxygen depletion and enhanced chlorophyll a levels follow the spatial pattern of total nitrogen levels in this system (Chapter VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment. The spatial pattern indicated that the magnitude of oxygen depletion, enhancement of chlorophyll a levels and total nitrogen concentrations increased with increasing distance from the tidal inlet, with highest nitrogen enrichment within the tidally restricted basins of Trapps Pond. Oxygen depletion, the magnitude of daily oxygen excursion and chlorophyll a levels indicate moderately nutrient enriched waters within critical regions of the main basin of Sengekontacket Pond, as well as Trapps Pond. The oxygen data is consistent with a moderate level of organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll a and macroalgae in some areas. While Majors Cove and Trapps Pond have the highest levels of nitrogen enrichment (tidally averaged TN of 0.375 and 0.382 mg N L-1, respectively), they both support eelgrass habitat, although with some impairment. While other areas presently support lower levels of watercolumn nitrogen, it appears from the accumulations of macroalgae (southern and northern portion of main Sengekontacket Pond) and measured oxygen depletion that the system has become organic matter enriched with impairments to eelgrass and benthic animal habitat.

Table VIII-1. Summary of nutrient related habitat quality within the Sengekontacket Pond Estuary within the Towns of Oak Bluffs and Edgartown, MA, based upon assessments in Section VII. WQMP: MVC Water Quality Monitoring Program

	Sengekontacket Pond Embayment System				
		Sengekontacket Pond			
Health Indicator	**Majors Cove**	**North**	**Mid**	**South**	**Trapps Pond**
Dissolved Oxygen	MI[1]	H/MI[2]	MI[3]	MI[4]	H/MI[5]
Chlorophyll	H[6]	H[7]	H[8]	H[9]	MI[10]
Macroalgae	H/MI[11]	MI[12]	MI [13]	MI/SI[14]	MI[15]
Eelgrass	MI/SI[16]	SI[17]	SI[18]	SI[18]	MI[19]
Infaunal Animals	H[20]	H[21]	H[22]	H/MI[23]	MI[24]
Overall:	**SI[25]**	**H/MI[17,26]**	**SI[25]**	**SI[27]**	**H/MI[28]**

1- oxygen levels always > 4mg/L , but 4-5 mg/L 28% of time and <6 mg/L 52% of time, WQMP
2- minimum 4.6 and 4.7 for WQMP stations Skt 1 and 2, respectively, appears to be similar to mid basin.
3- Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 63% and 15% of the 48 day record, although oxygen was always >4 mg L^{-1}
4- generally oxygen below 6 mg/L, infrequently below 4 mg/L, rarely below 3 mg/L Levels in excess of atmospheric equilibration small.
5- generally ~6 mg/L and above 5 mg/L 90% of record, with rarely<4 mg/L: WQMP minimum= 5.2 mg/L
6- levels low-moderate for a coastal basin, averaging 5 ug/L, maximum 13 ug/L, WQMP
7- levels low to moderate with averaging 3.5 and 3.9 ut/L for Skt-1 and 2, respectively, with a single event maximum of 20.5 and with all other samplings <11.8 ug/L (WQMP)
8- mooring average 5.2 ug L^{-1} only approaching ~10 ug L^{-1} on single event ; WQMP average 3.3 ug L^{-1}
9- moderately elevated averaging 6.2 ug/L and rarely exceeding 9 ug/L (mooring), record constant without major blooms; WQMP similar to mooring with average 5.3 ug L-1, maximum 13.6 ug L-1
10- moderate, mean= 10.9 ug/L, generally <16 ug/L, long term mean= 4.4 ug/L , maxi.= 8.4 ug/L WQMP
11- drift algae generally sparse, some moderately dense patches
12- areas of dense drift algae, some *Cladophora,* patches of attached *Codium*.
13- moderate density drift algae, patches of attached *Codium*.
14- extensive drift algae in places 10-30cm thick, *Cladophora* and a branched form, dense *Codium* areas
15 -- sparse drift algae, wide-spread thin algal mat (can alter infaunal habitat)
16- loss of large fringing beds in lower cove (SI) from 1951-1995, small beds remain upper cove (MI).
17- anecdotal qualitative evidence indicated historic eelgrass in this basin, however none exists presently
18 - loss of extensive eelgrass coverage from south 1/2 of main basin 1951-1995, no eelgrass in 2006
19- coverage in both basins, but heavy with epiphytes, no temporal data on changes in bed coverage
20- moderate numbers of individuals, moderate to high numbers of species, high diversity and Evenness; with crustaceans and mollusks, some deep burrowers.
21- community includes crustaceans and mollusks and some deep burrowers and organic enrichment tolerant species; high numbers of species and individuals, moderate to high diversity & Evenness
22- high numbers of individuals, species (25), diversity (>3) and Evenness (>0.7) some deep burrowers.
23- near inlet: high quality: high #'s of species, diversity (H') & Evenness (E), moderate #'s of individuals, some deep burrowers; rest of basin: moderate #'s species, H' & E, low to moderate #'s of individuals
24- moderate impaired benthic habitat, high numbers of individuals, low to moderate numbers of species, low diversity and Evenness, community dominated by amphipods.
25- impairment based on loss of extensive eelgrass habitat 1951-1998, still high quality infauna habitat
26- infauna with high species & individuals numbers, moderate to high diversity & Evenness, with crustaceans & mollusks & some deep burrowers, but some organic enrichment tolerant species; moderate oxygen depletion with low chlorophyll levels, but patches of accumulated drift algae
27- Significant Impairment based upon loss of eelgrass from basin variable quality benthic animal habitat, and areas of dense accumulations of drift algae.
28- significant eelgrass coverage, but with epiphytes; infauna dominated by amphipods indicating moderate organic enrichment; moderate chlorophyll levels & patches of thin algal mat
H = healthy habitat conditions; MI = Moderate Impairment; SI = Significant Impairment;
SD = Severe Degradation; -- = not applicable to this estuarine reach

Eelgrass habitat is clearly impaired throughout most of the system, which historically had extensive eelgrass coverage. At present, eelgrass exists only within a small portion of the system at the upper reaches of Major's Cove and in the inner and outer basins of Trapps Pond. The loss of the extensive eelgrass beds within the lower tidal reach of Majors Cove and throughout the southern 1/2 of Sengekontacket Pond between 1951 and 1998 (MassDEP Eelgrass Mapping Program), classifies these basins as significantly impaired. The persistence of eelgrass in the shallow waters of upper Majors Cove and within the tidally restricted basins of Trapps Pond (although heavily coated with epiphytes), classifies these areas as having moderate impairment. It appears that the remaining eelgrass beds within the Sengekontacket Pond Embayment System are restricted to shallow waters, where light can penetrate and possibly because oxygen depletion tends to be less in shallow rather than deep basins. It should be noted that even though there is no evidence that the northern portion of Sengekontacket Pond had eelgrass in the recent past, that should not lead managers to believe that this area has become impaired for this resource.

Although indictors generally show only moderate levels of nutrient enrichment, moderate oxygen depletion and chlorophyll levels, the depth of the basins also plays a role in determining the quality of the eelgrass habitat. The observed loss of eelgrass is consistent with the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion. Overall, the multi-basin decline of eelgrass beds relative to historical distributions is consistent given the moderate depths of these basins, periodic oxygen depletion, and presence of significant drift algae primarily within the lower 1/2 of Sengekontacket Pond. As a result of the significant loss of eelgrass habitat in this system, it is clear that management of the Sengekontacket Pond Embayment System must focus on nitrogen management for restoration of these resources.

Overall, the infaunal habitat quality in Sengekontacket Pond, Majors Cove and Trapps Pond was consistent with the observed levels of dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in each component of the system. Classification of habitat quality necessarily included the structure of the specific estuarine basin. Based upon this analysis it is clear that the tributary sub-embayment basin of Trapps Pond is presently supporting moderately impaired benthic habitat, while the northern and middle regions of the system and the area near the tidal inlet are supporting high quality habitat. Similarly, Majors Cove has benthic animal communities indicating high to slightly impaired habitat quality areas. In contrast, the southern basin of Sengekontacket Pond, south of the main tidal inlet, has spatially variable (patchy) infaunal animal communities. The community contains significant numbers of crustaceans and mollusks with some deep burrowers, but the numbers of individuals and species indicates impairment. It appears that the spatial variation may be associated with the large amount of drift algae present in summer throughout this southern basin.

In general, the habitat quality within the basins of this System is defined by the temporal changes in eelgrass coverage and benthic community characteristics, both of which are consistent with the observed levels of nitrogen and organic matter enrichment and the magnitude of oxygen depletion, as well as the sediment characteristics and macroalgal abundance and distribution. The distribution and levels of habitat impairment within the Sengekontacket Pond Embayment System is consistent with the low to moderate level of nitrogen enrichment. The loss of the extensive historical eelgrass coverage makes restoration of this resource the primary focus for nitrogen management, with the associated goal of restoring areas that have slightly impaired benthic habitat. The greater sensitivity of eelgrass (versus infauna) to nutrient related water quality declines and the need to restore eelgrass habitat within the innermost basins (Majors Cove, Trapps Pond) indicates that restoration of eelgrass habitat within the Sengekontacket Embayment System will also restore those areas with impaired benthic animal habitat. Determining the nitrogen targets to restoring these habitats is the focus of the nitrogen management threshold analysis, below.

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates that will support acceptable habitat quality throughout an embayment system is to first identify a sentinel location within the embayment and secondly, to determine the nitrogen concentration within the water column that will restore the location to the desired habitat quality. The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined (Section VIII.2), the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved (Section VIII.3). Siting the sentinel station within the Sengekontacket Pond Embayment System is different than in most estuaries, due to the presence of the tidally restricted sub-embayment of Trapps Pond. This tidal restriction disrupts the normal hydrodynamics and linkage to the other basins, functionally "isolating" Trapps Pond such that two (2) sentinel stations will be required in this estuary.

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Sengekontacket Pond Embayment System is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. Given the information on a variety of key habitat characteristics, it is possible to develop a site-specific threshold, which is a refinement upon more generalized threshold analyses frequently employed.

The Sengekontacket Pond Embayment System presently supports nitrogen related habitat impairment throughout the tidal reach. Eelgrass habitat is clearly impaired throughout most of the system, which historically had extensive eelgrass coverage. At present, eelgrass exists only within a small portion of the system at the upper reaches of Major’s Cove and in the inner and outer basins of Trapps Pond. The loss of the extensive eelgrass beds within the lower tidal reach of Majors Cove and throughout the southern 1/2 of Sengekontacket Pond between 1951 and 1998 classifies these basins as significantly impaired. The persistence of eelgrass in the shallow waters of upper Majors Cove and within the tidally restricted basins of Trapps Pond (although heavily coated with epiphytes), classifies these areas as having moderate impairment. It appears that the remaining eelgrass beds within the Sengekontacket Pond Embayment System are presently restricted to shallow waters, where light can penetrate and possibly because oxygen depletion tends to be less in shallow than deep basins.

The observed loss of eelgrass is consistent with the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion. The multi-basin decline of eelgrass beds is consistent with the basin depths, periodic oxygen depletion, and presence of significant drift algae primarily within the lower 1/2 of Sengekontacket Pond. As a result of the significant loss of critical eelgrass habitat throughout this estuarine system, the threshold nitrogen level was set to target eelgrass restoration as the primary habitat management goal.

While this system presently supports significantly impaired eelgrass habitat it also has basins with moderately impaired infaunal animal habitat. Trapps Pond is presently supporting moderately impaired benthic habitat, while the southern basin of Sengekontacket Pond, south of the main tidal inlet, has spatially variable (patchy) infaunal animal communities. Some of the variation in habitat quality within this basin is likely associated with the accumulation of large amounts of drift algae in some areas. In contrast, the northern and middle regions of the main basin of Sengekontacket Pond and the area near the main tidal inlet are supporting high quality habitat, while Majors Cove has benthic animal communities indicating high habitat quality to only slight impairment. The distribution and levels of habitat impairment within the Sengekontacket Pond Embayment System is consistent with the low to moderate level of nitrogen enrichment. Keeping the current state of eelgrass and infaunal habitat, at present, eelgrass habitat is impaired at TN levels at the sentinel stations of 0.375 and 0.382 mg N L^{-1} (tidally averaged).

The loss of eelgrass at low to moderate levels of nitrogen enrichment was also quantified in nearby Lagoon Pond. In that system, eelgrass has been significantly declining in coverage at tidally averaged nitrogen (total nitrogen, TN) levels of 0.378 mg N L^{-1} and 0.385 mg N L^{-1}, respectively. Additionally, in Lagoon Pond some stable eelgrass beds exist within the lower basin at tidally averaged nitrogen levels of 0.328 mg N L^{-1}, while fringing eelgrass beds presently exist in the shallow margins of the upper and mid basin at nitrogen levels between 0.371 mg N L^{-1} and 0.338 mg N L^{-1}, although loss is occurring at the higher N level. These TN levels and patterns of habitat stability/decline are consistent with persistence and loss of eelgrass at similar depths in other estuaries on Vineyard/Nantucket Sound. In Waquoit Bay at similar depths, eelgrass was found to slowly decline at average TN concentrations of 0.395 mg L^{-1} (lower basin of Waquoit Bay) and was lost from the Centerville River also at a tidally averaged TN of 0.395 mg L^{-1}. In the West Falmouth Harbor Estuary on Buzzards Bay, eelgrass declined when nitrogen enrichment resulted in levels over 0.35 mg L^{-1}. It should be noted that water depth is important in determining the threshold nitrogen level for eelgrass, as the same phytoplankton concentration that results in shading of eelgrass in deep water, will allow sufficient light to support eelgrass in shallow water. The need for a lower threshold in deeper (~2 meter) versus shallower (<1 meter) water has been seen in a number of MEP assessments, a good example being the assessment of Bournes Pond, Falmouth.

It appears that the threshold for stable eelgrass habitat at depth in the main basins of the Sengekontacket Pond Embayment System nitrogen levels must be less than 0.378-0.385 mg N L^{-1}, as these areas are presently impaired and between 0.371 mg N L^{-1} and 0.338 mg N L^{-1}. Based upon these observations and those from other systems, a tidally averaged nitrogen threshold for Sengekontacket Pond of 0.35 mg N L^{-1} will allow restoration of the impaired eelgrass habitat. This threshold is similar to that for West Falmouth Harbor and Phinneys Harbor, and is focused in part on restoring eelgrass at depth (~2 m) as found historically. This threshold is for the sentinel stations SKT-4 and SKT-9, located in the upper reach of Majors Cove and at the culvert to Trapps Pond. The stations are situated to target eelgrass restoration and both are part of the MVC Water Quality Monitoring Program.

Lowering the level of nitrogen enrichment at the sentinel station will lower nitrogen levels throughout the estuary (Section VIII.3) with the parallel effect of improving infaunal habitat quality. Therefore, the goal is to achieve the nitrogen target at the sentinel location(s) and restore the historical eelgrass habitat within Sengekontacket Pond. This will necessarily also result in the restoration of infaunal habitat throughout the System. Nitrogen management for the restoration of eelgrass and infaunal habitat quality within the Sengekontacket Pond Embayment System will likely include source reduction within the watershed and possibly increasing tidal flushing of Trapps Pond, which is presently experiences significantly restricted tidal exchange at the inlet culvert. The nitrogen loads associated with the threshold concentration at the sentinel locations and secondary infaunal check stations are discussed in Section VIII.3 (below).

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Sengekontacket Pond System. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for the Sengekontacket Pond System (SKT-4 is located in the head of Majors Cove and SKT-9 is located at the outlet from Trapps Pond within the main basin of Sengekontacket Pond). It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required using: 1) removal of 60% of the septic nitrogen load from Majors Cove watershed (watershed 2) with 2) the removal of 100% of septic nitrogen loading from Trapps Pond watershed (watershed 4). The Trapps Pond watershed does not contain a significant amount of development, however due to the limited tidal flushing occurring between the two shallow basins that comprise Trapps Pond and the main Sengekontacket Pond basin there was no other alternative available to meet the nitrogen threshold without physically altering the culverts within Trapps Pond. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

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

sub-embayment	present septic load (kg/day)	threshold septic load (kg/day)	threshold septic load % change
Farm Neck	5.696	5.696	0.0%
Majors Cove[1]	9.392	4.134	-56.0%
Ocean Heights	10.940	10.940	0.0%
Trapps Pond	2.036	0.000	-100.0%
State Beach	0.0	0.0	0.0%

[1] Majors Cove is a combination of Majors Cove watershed (watershed 2), and Fresh Pond watershed (watershed 5) thus the 60% reduction in septic loading for the threshold does not result in a direct 60% reduction in septic loading.

Figure VIII-1. Contour plot of modeled average total nitrogen concentrations (mg/L) in Sengekontacket Pond system, for threshold conditions (0.35 mg/L at water quality monitoring stations SKT-4 and SKT-9), to restore eelgrass habitat within Majors Cove/Sengekontacket Pond and to improve eelgrass habitat within Trapps Pond. The approximate locations of the sentinel threshold stations for Sengekontacket Pond (SKT-4 and SKT-9) are shown. There is no baseline water quality station within Trapps Pond.

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. Removal of septic loads from Majors Cove and Trapps Pond results in the total nitrogen loads presented in Table VIII-4. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent ‘worst-case’ summertime conditions. The benthic flux for this modeling effort is reduced from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in the adjacent waters of Nantucket Sound.

Table VIII-3. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Sengekontacket Pond 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
Farm Neck	9.392	9.392	0.0%
Majors Cove	11.627	6.370	-45.2%
Ocean Heights	13.260	13.260	0.0%
Trapps Pond	3.175	1.140	-64.1%
State Beach	0.115	0.115	0.0%

Table VIII-4. Threshold sub-embayment loads and attenuated surface water loads used for total nitrogen modeling of the Sengekontacket Pond system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	threshold load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Farm Neck	9.392	3.337	-0.896
Majors Cove	6.370	1.189	4.709
Ocean Heights	13.260	5.932	-14.623
Trapps Pond	1.140	0.660	2.372
State Beach	0.115	-[1]	1.598

[1] Atmospheric deposition for State Beach is including within the atmospheric deposition for Ocean Heights

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel stations is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, a reduction in TN concentration of approximately 6% and 8% were required at station SKT-4 and SKT-9, respectively.

The basis for the watershed nitrogen removal strategy utilized to achieve the embayment thresholds may have merit, since this example nitrogen remediation effort is focused on watersheds where groundwater is flowing directly into the estuary. For nutrient loads entering the systems through surface flow, natural attenuation in freshwater bodies (i.e., streams and ponds) can significantly reduce the load that finally reaches the estuary. Presently, this attenuation is occurring due to natural ecosystem processes and the extent of attenuation being determined by the mass of nitrogen which discharges to these systems. The nitrogen reaching these systems is currently “unplanned”, resulting primarily from the widely distributed non-point nitrogen sources (e.g. septic systems, lawns, etc.). Future nitrogen management should take advantage of natural nitrogen attenuation, where possible, to ensure the most cost-effective nitrogen reduction strategies. However, “planned” use of natural systems has to be done carefully and with the full analysis to ensure that degradation of these systems will not occur.

One clear finding of the MEP has been the need for analysis of the potential associated with restored wetlands or ecologically engineered ponds/wetlands to enhance nitrogen attenuation. Attenuation by ponds in agricultural systems has also been found to work in some cranberry bog systems, as well. Cranberry bogs, other freshwater wetland resources, and freshwater ponds provide opportunities for enhancing natural attenuation of their nitrogen loads. Restoration or enhancement of wetlands and ponds associated with the lower ends of rivers and/or streams discharging to estuaries are seen as providing a dual service of lowering infrastructure costs associated with wastewater management and increasing aquatic resources associated within the watershed and upper estuarine reaches.

Table VIII-5. Comparison of model average total N concentrations from present loading and the modeled threshold scenario, with percent change, for the Sengekontacket Pond system. Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Farm Neck Inlet	Skt-1	0.308	0.306	-0.6%
Farm Neck Basin	Skt-2	0.320	0.317	-0.9%
Majors Cove	Skt-3	0.351	0.336	-4.0%
Majors Cove	**Skt-4**	**0.375**	**0.354**	**-5.6%**
Main Inlet	Skt-5	0.299	0.298	-0.4%
Ocean Heights	Skt-6	0.308	0.306	-0.8%
Ocean Heights	Skt-7	0.306	0.304	-0.7%
Ocean Heights	Skt-8	0.331	0.322	-2.5%
Trapps Pond	**Skt-9**	**0.382**	**0.352**	**-8.0%**

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.

IX. ALTERNATIVES TO IMPROVE WATER QUALITY

At the request of Town of Edgartown, MEP staff completed an additional scenario (Scenario 1) based upon planned wastewater nitrogen load reduction in the Sengekontacket Pond watershed. Specifically, the Town requested that the MEP Technical Team assess the impact of collecting wastewater within the planned Ocean Heights/ Arbutus Park sewer area (Figure IX-1). Under this scenario, existing wastewater within this sewer area, which is completely contained within the Ocean Heights subwatershed, is collected and treated at the Edgartown Waste Water Treatment Facility (WWTF) and the treated effluent returned to a discharge site within the same subwatershed. The existing measured flow from the properties within the proposed sewer collection area is estimated to be 84,543 gallons per day and the measured total nitrogen concentration in the effluent from the Edgartown WWTF is 2.97 mg/l. This WWTF treatment level is based on flow-weighted effluent data from January 2007 through September 2010 and the individual properties selected were based on a GIS coverage provided by the Town.

IX.1 LOADING SCENARIO 1

Based on the potential sewer area developed by the Town of Edgartown under their ongoing CWMP process, a revised “existing conditions”, watershed nitrogen loading scenario was developed and assessed using the calibrated and validated Linked Watershed Embayment Management Modeling Approach. Wastewater flows were developed under loading scenarios as described in Chapter 6. Table IX-1 and Table IX-2 illustrate the overall change to septic and watershed loads resulting from implementing this wastewater planning alternative. Based on the assumptions developed for this Scenario, Table IX-3 presents the various components of nitrogen loading for the Sengenkontacket Pond system. Although there will be a significant reduction (-61%) in the wastewater related nitrogen loading (-50% reduction in total watershed N load) from the Ocean Heights/Arbutus Park region of the watershed, this reduction in not sufficient by itself in fully restoring the nitrogen impairment to the Sengekontacket Pond System. The threshold target (0.35 mg/L TN at station SKT-4 and SKT-9) is not reached at the sentinel stations. However, improvements are seen in many of the basins, particularly in the sub-basin adjacent Ocean Heights and its associated sub-basin of Trapps Pond

Table IX-1. Comparison of sub-embayment watershed ***wastewater loads*** (attenuated) used for modeling of present loading conditions for Scenario 1. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.

sub-embayment	present septic load (kg/day)	Scenario 1 Wastewater (septic + WWTF) load (kg/day)	Scenario 1 wastewater load % change
Farm Neck[1]	5.696	5.721	0.4%
Majors Cove	9.392	9.392	0.0%
Ocean Heights	10.940	4.236	-61.3%
Trapps Pond	2.036	2.036	0.0%
State Beach	0.000	0.000	0.0%

[1] MVC revised the present watershed loading at the Landfill for the Farm Neck watershed after the initial report was published.

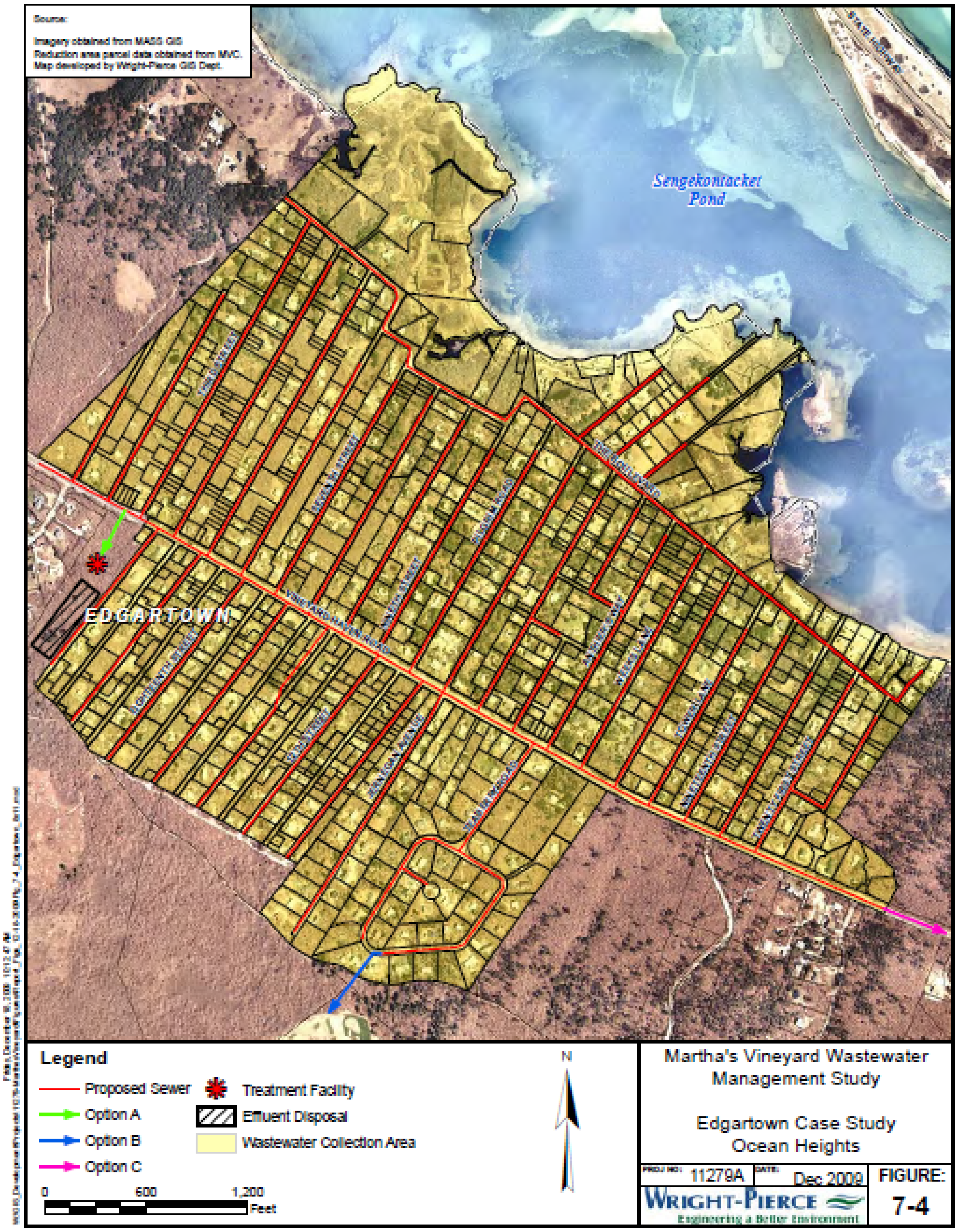

Figure IX-1. Ocean Heights/ Arbutus Park sewer area. Under Scenario 1, existing wastewater flows from this area are collected, treated at the Edgartown WWTF and discharged at the location shown in the figure. The sewer area is completely contained within the Ocean Heights subwatershed. The collected water use in this area is 84,543 gallons per day and the measured total nitrogen concentration in the effluent from the Edgartown WWTF is 2.97 mg/l. This figure is from the Martha's Vineyard Wastewater Management Study (Wright-Pierce, 2009).

Table IX-2. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Scenario 1. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	% change
Farm Neck[1]	9.392	9.416	0.3%
Majors Cove	11.627	11.627	0.0%
Ocean Heights	13.260	6.556	-50.6%
Trapps Pond	3.175	3.175	0.0%
State Beach	0.115	0.115	0.0%

[1] MVC revised the present watershed loading at the Landfill for the Farm Neck watershed after the initial report was published.

Table IX-3. Sub-embayment loads used for total nitrogen modeling of the Sengekontacket Pond System for present loading scenario with loading modified to represent Scenario 1, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	scenario watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Farm Neck	9.416	3.337	-0.896
Majors Cove	11.627	1.189	4.746
Ocean Heights	6.556	5.932	-14.623
Trapps Pond	3.175	0.660	3.276
State Beach	0.115	-[1]	1.598

[1] Atmospheric deposition for State Beach is including within the atmospheric deposition for Ocean Heights

Table IX-4. Comparison of model average total N concentrations from present loading (with and without the reduction of septic loads for Scenario 1), with percent change, for the Sengekontacket Pond system. Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	Scenario 1 (mg/L)	% change
Farm Neck Inlet	Skt-1	0.308	0.307	-0.1%
Farm Neck Basin	Skt-2	0.320	0.320	-0.2%
Majors Cove	Skt-3	0.351	0.349	-0.5%
Majors Cove	**Skt-4**	**0.375**	**0.373**	**-0.7%**
Main Inlet	Skt-5	0.299	0.298	-0.4%
Ocean Heights	Skt-6	0.308	0.306	-0.8%
Ocean Heights	Skt-7	0.306	0.302	-1.1%
Ocean Heights	Skt-8	0.331	0.322	-2.5%
Trapps Pond	**Skt-9**	**0.382**	**0.374**	**-2.1%**

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