Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Menemsha-Squibnocket Pond Embayment System, Wampanoag Tribe, the Towns of Chilmark & Aquinnah, MA

University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

DRAFT REPORT – JUNE 2017

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I. INTRODUCTION

The Menemsha-Squibnocket Pond Embayment System is a complex estuary located within the Town of Chilmark and Aquinnah on the island of Martha's Vineyard, Massachusetts with a southern shore bounded by water from the Atlantic Ocean (Squibnocket Pond) and a north shore bounded by Vineyard Sound (Figure I -1). The Menemsha-Squibnocket Pond watershed is distributed across the Towns of Chilmark and Aquinnah and are shared by the Wampanoag Tribe of Aquinnah. Land-uses closest to an embayment generally have greater impact than those in the upper portions of the watershed, which can support attenuation of nitrogen during transport through natural aquatic systems (e.g. ponds, rivers, wetlands etc.) prior to discharge to the embayment. However, effective nutrient management for protection/restoration of the Menemsha-Squibnocket Pond Embayment System will require consideration of all sources of nitrogen load throughout the entire watershed. That the open water basins and the entire watershed to the system is contained within only two towns will make development and implementation of a comprehensive nutrient management and protection/restoration plan a little more simple as the challenges are reduced due to the lack of potentially conflicting municipal constraints and regulations.

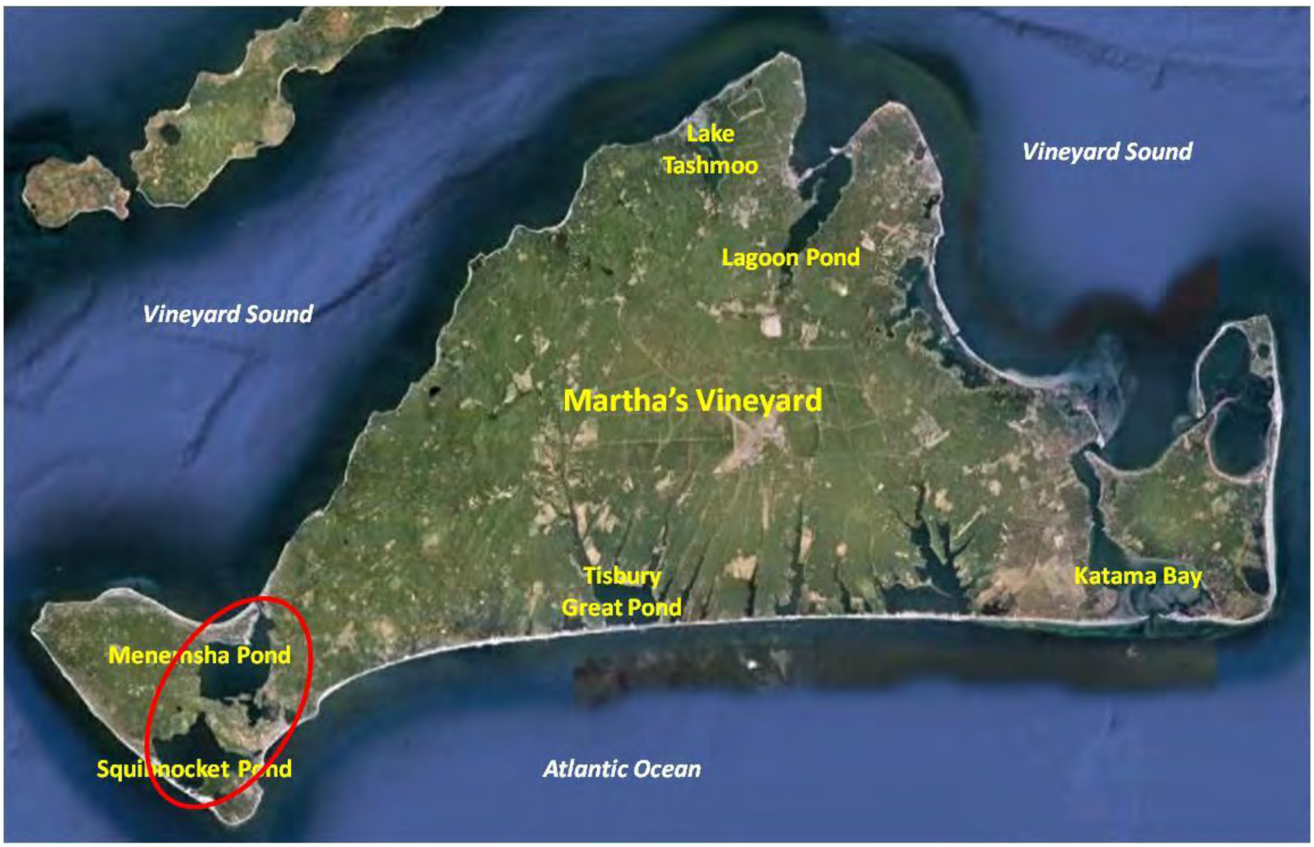

Figure I-1. Location of the Menemsha-Squibnocket Pond Embayment System, Island of Martha's Vineyard, Town of Chilmark and Aquinnah, Massachusetts. Menemsha Pond is a great salt pond with an open and permanent armored inlet that supports free exchange of water through a barrier beach. Squibnocket Pond does not have an inlet directly to the Atlantic Ocean but rather has an open interconnection with Menemsha Pond via a herring creek.

The nature of enclosed embayments in populous regions brings two opposing elements to bare: as protected marine shoreline they are popular regions for boating, recreation, and land development; as enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shores. The multiple coves and sub-embayments to the Menemsha-Squibnocket Pond Embayment System greatly increases the shoreline and decreases the travel time of groundwater (and its pollutants) from the watershed recharge areas to bay regions of discharge. As such, the estuary is particularly vulnerable to the effects of nutrient enrichment from the watershed, especially considering that circulation is mainly through wind driven mixing in Squibnocket Pond and limited exchange / flushing of Nashaquitsa Pond and Stonewall Pond with "clean" Vineyard Sound water. In particular, the Menemsha-Squibnocket Pond Embayment System and its sub-embayments along the north/south shore of Martha's Vineyard are at risk of eutrophication (over enrichment) from nitrogen enriched groundwater and surface water flows and runoff from the watershed should development pressure increase.

The Menemsha-Squibnocket Pond Embayment System is a complex coastal open water embayment comprised of a large northern basin (Menemsha Pond) that is connected to a smaller basin on the southeastern side (Nashaquitsa Pond) which in turn is connected via a shallow channel to a terminal basin (Stonewall Pond). Menemsha Pond exchanges water directly with Vineyard Sound / Menemsha Bight via Menemsha Channel and an inlet that is armored to both the east and west. In addition, Squibnocket Pond is hydraulically connected to Menemsha Pond via a herring creek that passes through a culvert under State Road. Squibnocket Pond does not support an inlet directly to the Atlantic Ocean. Rather, it likely receives periodic overwash of Atlantic Ocean water during significant storm events. The Squibnocket Pond portion of the system is maintained as an estuary by the periodic overwash of the barrier beach as well as limited tidal exchange with estuarine waters of Menemsha Pond via the herring creek (Figure I-2). Additionally, both Menemsha Pond and Squibnocket Pond receive fresh groundwater from the surrounding watershed as well as to a more limited extent from three small surfacewater discharges (Black Brook into Squibnocket Pond, and two creek discharges into Menemsha Pond, one at Pease Point and the other into Menemsha Inner Basin). At present the extent of tidal exchange between Squibnocket Pond and Menemsha Pond plays a fundamental role in the maintenance of nutrient related water quality and habitat health throughout this portion of the estuary.

The present Menemsha-Squibnocket Pond Embayment System results from a complex geologic history dominated by glacial processes occurring during the last glaciation of the southeastern Massachusetts region. The late Wisconsinan Laurentide ice sheet reached its maximum extent and southernmost position about 20,000 years before present (BP), as indicated by the presence of terminal moraines on 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 main part of Cape Cod was deposited as the Barnstable outwash plain. The watershed to the Menemsha-Squibnocket Pond Embayment System is composed primarily of both moraine deposits with the possibility of sandy outwash plain at the eastern most edges (Figure I-3).

As the ice sheet retreated and a glacial lake occupied Nantucket Sound, the glacial meltwater lake occupying what is now considered Nantucket Sound is likely to have had a profound effect on the geomorphology of Menemsha and Squibnocket Ponds, shaping the topography and setting the stage for the formation of coastal salt ponds and estuaries as sea level rose and the land surface rebounded. On Martha's Vineyard, the topographic depressions that contain Menemsha Pond and Squibnocket Pond, as well as those that contain Vineyard Haven Harbor and Edgartown and Katama Bay, all developed over lows in the preglacial surface that lies atop the coastal plain and moraine deposits. The passages through the Elizabeth Islands opposite Menemsha Pond, called holes (for example Quicks Hole and Woods Hole), may also have developed over lows in the surface beneath the drift.

Many coastal ponds such as Menemsha Pond, Squibnocket Pond, Chilmark Pond, Tisbury Great Pond and Edgartown Great Pond, have been managed since colonial times, when settlers discovered that temporarily breaching baymouth bars increased the salinity of ponds and provided good habitats for shellfish, particularly oysters, and finfish. This was confirmed in a 1990 planning and management study of Squibnocket Pond as a coastal resources (Gaines and Broadus, 1990) which presented historic documentation that an intermittent breachway existed through the barrier beach separating Squibnocket Pond from the Atlantic. The earliest record of such an inlet to Squibnocket Pond is found in the DeBarres map dating back to 1776. As documented in Gaines, 1990, "no other map found portrays this feature, although the 1831 Dunham map marks the same site, 'opening formerly here'." Of equal importance to the future management of the system is the documentation that the herring creek connection between Menemsha Pond and Squibnocket Pond was man-made showing that in both the DeBarres Map (1776) and the Pease Map (1866), the present herring creek terminated a short distance inland from its mouth on the northern shore of Squibnocket Pond suggesting the present connection to Menemsha Pond occurred later (Gaines and Broadus, 1990). It should also be noted that the inlet to Menemsha Pond is also a significantly altered feature and that should be factored into future management decisions regarding maintaining or maximizing exchange of water between Menemsha Pond and Vineyard Sound. The man-made nature of the inlet to Menemsha Pond is highlighted by the Martha's Vineyard Gazette article on coastal erosion wherein the writer of the article stated, "On the Island, the first grand efforts to engineer things along the coastline began at the start of the 1900s. As part of a huge statewide effort costing $70 million, the board of harbor and land commissioners authorized the opening of a freshwater lake at Oak Bluffs and <u>the dredging of a creek at Menemsha to create the harbors known there today</u>."

The basins of the Menemsha-Squibnocket Pond Embayment System were formed by coastal processes forming a barrier beach along the open basin front to the Atlantic Ocean (Squibnocket Pond) as well as the barrier beach along the basin front to Vineyard Sound (Menemsha Pond). These basins are properly termed lagoons (e.g. lagoonal estuarine basins) and run parallel to the coast behind the sandy barrier. The formation and structure of the Squibnocket Pond portion of the overall embayment system parallels that of its larger neighbors, Chilmark Pond, Tisbury Great Pond and Edgartown Great Pond.

The formation of the Menemsha-Squibnocket Pond Embayment System has been and continues to be greatly affected by coastal processes, specifically the role that the barrier beach plays in separating Squibnocket Pond from Atlantic Ocean waters as well as the degree of infilling of the tidal inlet and channel connecting Menemsha Pond to Vineyard Sound. The ecological and biogeochemical structure of Menemsha Pond prior to the armoring of the inlet is likely to have changed over time as the barrier beach has migrated, breached and closed as a function of high pond levels (freshwater inflow) and storm frequency and intensity. This is particularly the case with Squibnocket Pond which is presently closed to the Atlantic Ocean. It is almost certain that the closed basin of Squibnocket Pond is geologically a recent phenomenon, and that the pond was more generally open during lower stands of sea level and disconnected from Menemsha Pond.

Figure I-2. Study region for the Massachusetts Estuaries Project analysis of the Menemsha-Squibnocket Pond Embayment System. Tidal waters from Vineyard Sound enter Menemsha Pond through an armored inlet. A herring creek connects Squibnocket Pond to Menemsha Pond allowing limited tidal exchange between the two basins. The barrier beach that separates Squibnocket Pond from the Atlantic Ocean is not periodically breached however overwash of the beach does occur under storm conditions.

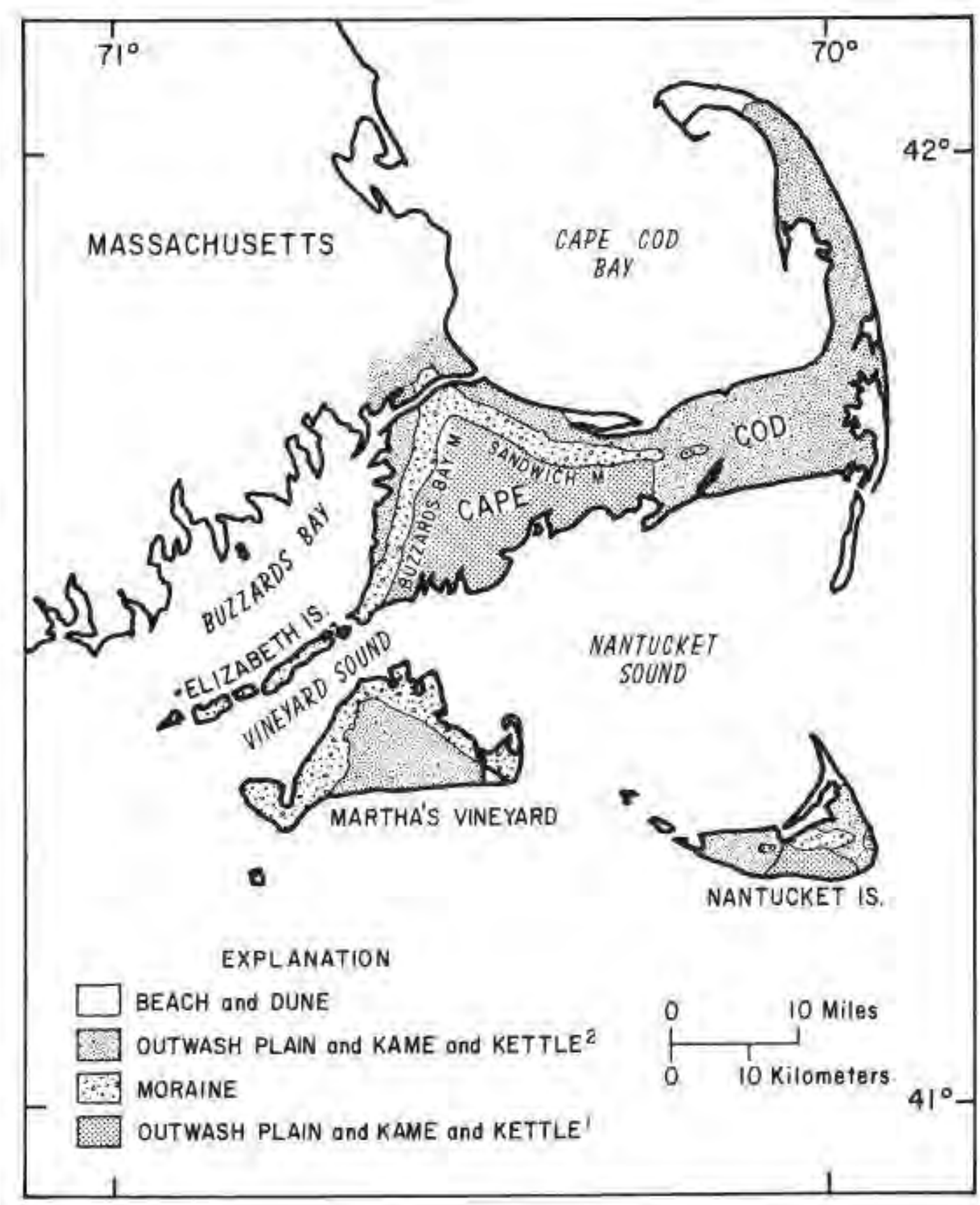

Figure I-3. Generalized geologic map of study region (Cape Cod and Islands) for the Massachusetts Estuaries Project analysis of the Menemsha-Squibnocket Pond Embayment System (Oldale, 1992).

The Menemsha Pond portion of the Embayment System is a 790 acre (depending on the water level in the pond) coastal salt pond whereas Squibnocket Pond is a 603 acre coastal pond. The watershed to Menemsha Pond is ~1856 acres whereas the watershed to Squibnocket Pond is ~ 1303 acres. Generally, the watershed to the Menemsha-Squibnocket Pond Embayment System is situated in moraine deposits with the possibility that as one moves towards the eastern edge of the overall watershed, sediment become more a mix of moraine and sandy outwash material. The eastern sub-watersheds discharge freshwater to the estuary via groundwater flows and two small creeks, while the western sub watersheds which also generates both groundwater and surfacewater (Black Brook) formed within the moraine. Squibnocket Pond receives surfacewater inflow from Black Brook which is primarily a groundwater fed stream. Menemsha Pond receives surfacewater inflow from a small creek discharging at Pease Point as well as from a small creek that flows into a small salt marsh adjacent the Menemsha Inner Basin close to the inlet. For the MEP analysis, the Menemsha-Squibnocket Pond estuarine system was partitioned into two general sub-embayment groups: 1) Menemsha Pond (inclusive of Nashaquitsa Pond and Stonewall Pond) and 2) Squibnocket Pond (see Figure I-2).

The primary ecological threat to the Menemsha-Squibnocket Pond Embayment System as a coastal resource is degradation resulting from nutrient enrichment. Nutrient enrichment generally occurs through increases in watershed nitrogen loading resulting from changing land uses (typically conversion of pine/oak forest to residential development) and/or reduced tidal exchanges with offshore waters. Although it is possible that portions of Menemsha and Squibnocket Ponds can have periodic issues relative to bacterial contamination primarily within the most enclosed regions of each, fecal coliform contamination does not generally result in ecological impacts, rather it is associated with public health concerns related with consumption of potentially contaminated shellfish. The primary impact of bacterial contamination is the closure of shellfish harvest areas, rather than the destruction of shellfish and other marine habitats. In contrast, increased loading of the critical eutrophying nutrient (nitrogen) to the Menemsha-Squibnocket Pond Embayment System results in both habitat impairment and loss of the resources themselves. Within the watershed of this complex salt pond system, nitrogen loading has been increasing as land-uses have changed over the past 60 years. The nitrogen loading to this system, like almost all embayments in southeastern Massachusetts and the Islands, results primarily from on-site disposal of wastewater, agriculture (animal and plant) and fertilizer applications (residential and agricultural), and to a lesser extent stormwater flows. Nitrogen enrichment of all coastal embayments can only be managed through lowering inputs or increasing the rate of loss through tidal flushing. This is discussed in detail in Sections IV.1 and VI.

The Towns of Martha's Vineyard have been among the fastest growing towns in the Commonwealth over the past two decades and unlike the Town of Edgartown, which has a centralized wastewater treatment system with the site of discharge of its tertiary treated effluent being located in the Edgartown Great Pond watershed, the Town of Chilmark and Aquinnah does not have such a wastewater system servicing the watersheds of Menemsha or Squibnocket Ponds. Rather, treatment of wastewater within the watershed to the embayment system is by privately maintained on-site septic systems for treatment and disposal of wastewater. As existing and likely increasing levels of nutrients impact the coastal embayments of the Towns of Chilmark and Aquinnah, water quality degradation will accelerate, with further harm to valuable aquatic resources of the Town and the Island on the whole.

As the primary stakeholders to the Menemsha-Squibnocket Pond Embayment System, the Wampanoag Tribe along with the Towns of Chilmark and Aquinnah, in collaboration with the Martha's Vineyard Commission (MVC), were among the first communities on Martha's Vineyard to become concerned over perceived degradation of their coastal embayments. Over the years, this local concern has led to the conduct of several studies (see Section II) of nitrogen loading to the system such as the Martha's Vineyard Commission developed Nutrient Loading and Management Plan of Chilmark, Menemsha and Squibnocket Ponds, (MVC, 2001). Key in this effort has been the Water Quality Monitoring Program of Martha's Vineyard's estuaries, 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 (2000, 2002, 2003, 2012) required for the implementation of the MEP's Linked Watershed-Embayment Approach used in the present study.

Since the initial results of the historic Water Quality Monitoring Program indicated that parts of the Menemsha-Squibnocket Pond Embayment System were showing signs of impairment and poor water quality, presumably due to land-derived nitrogen inputs, the Martha's Vineyard Commission (MVC) undertook additional site-specific data collection that has served to support MEP's ecological assessment and modeling effort. The common focus of the MVC work related to the Menemsha-Squibnocket Pond Embayment System has been to gather site-specific data on the current nitrogen related water quality throughout the estuary and determine its relationship to watershed nitrogen loads (e.g. Martha's Vineyard Commission Nutrient Load to Menemsha Pond, Squibnocket Pond and Chilmark Pond, 2001 {updated in 2010}). The multi-year water quality monitoring effort has provided the baseline information required for calibrating and verifying the water quality model linking upland loading, periodic tidal flushing, and estuarine water quality. The MEP effort builds upon the Water Quality Monitoring Program results and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the restoration of this embayment system. These critical nitrogen threshold levels and the link to specific ecological criteria form the quantitative basis for the nitrogen loading targets necessary for nitrogen management plans and the development of cost-effective alternatives for protection/restoration of habitat impaired by nitrogen enrichment needed by the Towns of Chilmark and Aquinnah as well as the Tribe.

While the completion of this complex multi-step process of rigorous site-specific 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 and Tribal staff and volunteers over many years and members of the Martha's Vineyard Commission. The modeling tools developed as part of this program provide the quantitative information necessary for the Wampanoag Tribe, the Town of Chilmark and the Town of Aquinnah to develop and evaluate the most cost effective nitrogen management alternatives to protect / restore this valuable coastal resource which is currently being gradually degraded by nitrogen overloading. It is important to note that the Menemsha-Squibnocket Pond Embayment System and its associated watershed have been 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, protection / restoration of this system should focus on managing nitrogen through both management of nitrogen loading within the watershed, restoration/management of processes which serve to lessen the amount or impact of nitrogen entering the estuary and inlet / channel maintenance to maximize the rate of nitrogen removal from the estuary via tidal flushing. As Squibnocket Pond has limited exchange with Menemsha Pond, it may be necessary to consider periodic openings to the Atlantic Ocean similar to what is undertaken in Chilmark Pond and Tisbury Great Pond.

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 their ability to assimilate additional nutrient inputs without decline 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 and the Islands alone, almost all of the municipalities (as is the case with the Town of Chilmark and Aquinnah) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries, often resulting from nutrient over-enrichment.

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) for those estuarine systems that are presently impaired by nitrogen enrichment or which will become impaired as build-out of their watershed continues. 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 Town 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 related health and nutrient sensitivity of each of the embayments in southeastern Massachusetts
- 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 65+ 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-4). This methodology integrates a variety of field data and models, specifically:

- Water column 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 attenuated nitrogen load
    - land-use analysis (GIS)
    - watershed N model

- Embayment TMDL - Synthesis
    - linked Watershed-Embayment N Model
    - salinity surveys (for linked model validation)
    - rate of N recycling within embayment
    - D.O record
    - Macrophyte survey
    - Infaunal survey

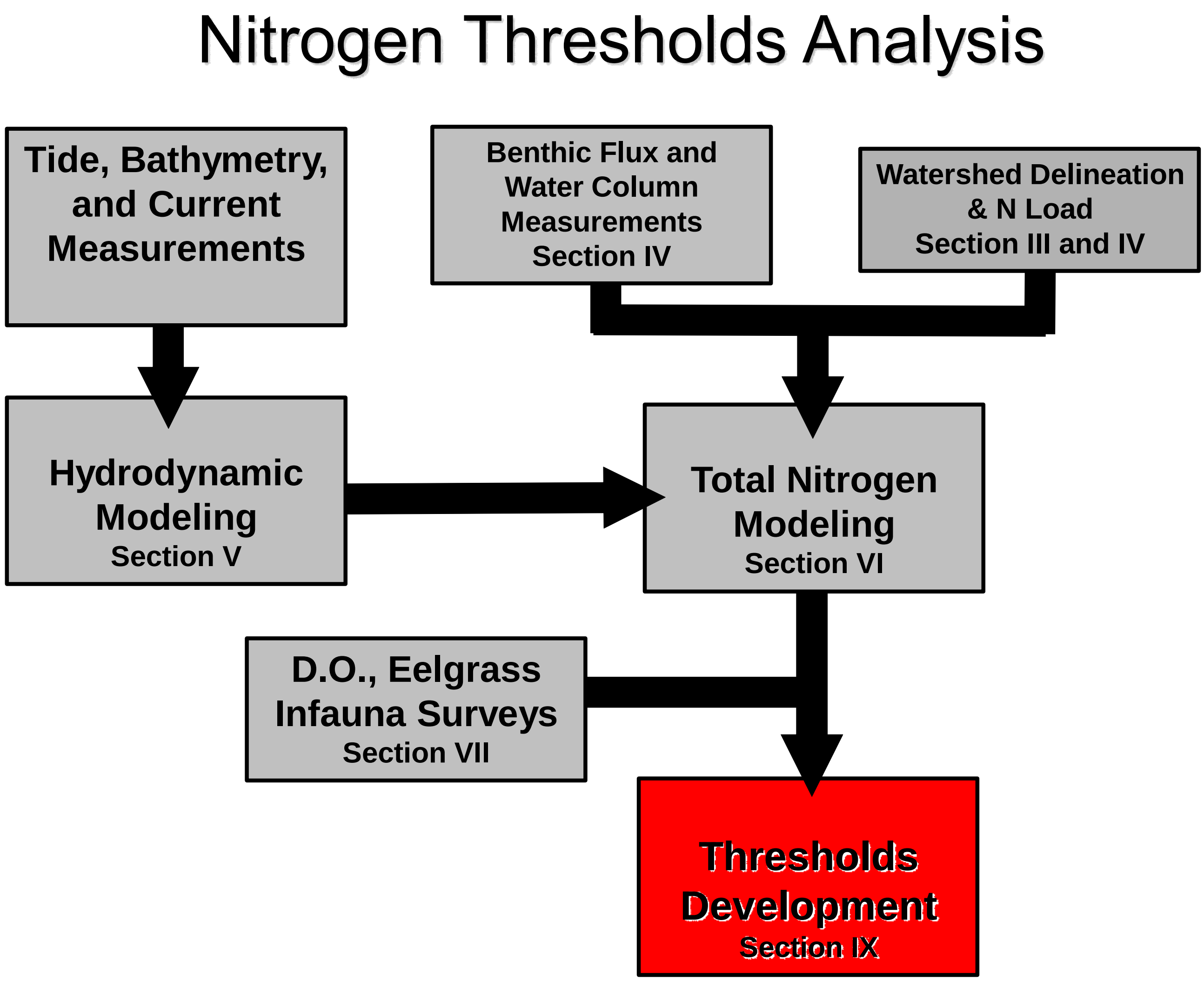

Figure I-4. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach.

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 Menemsha-Squibnocket Pond Embayment 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 Menemsha-Squibnocket Pond Embayment System follow this general pattern, with the Redfield Ratio (N/P) averaging <16, but with total dissolved inorganic nitrogen levels quite low indicating that addition of nitrogen would have a stimulatory effect of plant production.

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

Each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation. However, as loading increases a point is reached at which the capacity (termed assimilative capacity) is exceeded and nutrient related water quality degradation occurs. This point can be termed the “nutrient threshold” and in estuarine management this threshold sets the target nutrient level for restoration or protection. Because nearshore coastal salt ponds and embayments are the primary recipients of nutrients carried via surface and groundwater transport from terrestrial sources, it is clear that activities within the watershed, often miles from the water body itself, can have chronic and long lasting impacts on these fragile coastal environments.

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

Fortunately, a number of estuarine reaches within the Menemsha Pond portion of the system are near or only slightly beyond their ability to assimilate additional nutrients without impacting their ecological health. Nitrogen levels are elevated in the upper reaches of Menemsha Pond (e.g. Nashaquitsa Pond and Stonewall Pond) and eelgrass beds have been lost (~25% from 1995 to 2006) over the past ~50 years as indicated by the MassDEP Eelgrass Mapping Program and as confirmed by the MEP Technical Team during the summer and fall of 2007. In addition, nitrogen related habitat impairment within the Squibnocket Pond system is relatively uniform and consistent with the nitrogen levels as well as biologic indicators of habitat health. The result is that nitrogen management of the primary sub-embayments to the Menemsha-Squibnocket Pond

Embayment System is aimed at restoration and protection/maintenance of existing conditions, depending on the state of specific areas of the overall system.

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 this embayment system and contributed to its slight decline in ecological health, the Menemsha-Squibnocket Pond basins, like others analyzed by the MEP such as Lake Tashmoo, Lagoon Pond and Sengekontacket Pond, are especially sensitive to nitrogen inputs, because of the reduced tidal exchange (particularly Nashaquitsa Pond, Stonewall Pond and Squibnocket Pond). The quantitative role of the discontinuous tidal exchange of this system, as a natural process, was also considered in the MEP nutrient threshold analysis. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a “pristine” system.

I.3 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” (e.g. watershed derived and offshore nutrient inputs) for water quality modeling of the Menemsha-Squibnocket Pond Embayment System; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within each component of the overall 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 Menemsha-Squibnocket Pond Embayment System, including the tributary sub-embayments of Nashaquitsa Pond and Stonewall Pond. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents at the Menemsha Pond inlet and water elevations was employed for the system. Additionally, the quantification of the tidal flux of water and nutrients within the Herring Creek connecting Menemsha Pond to Squibnocket Pond was taken into consideration in the overall hydrodynamic and water quality analysis. Once the hydrodynamic properties of each estuarine basin were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates and under present circulation patterns.

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 and based upon MVC/MEP refined watershed and subwatershed delineations. The delineations were developed relative to: 1) water table contours measured in a few locations (*e.g.*, Wilcox, 1996) and modeled throughout the outwash plain and 2) USGS topographic maps in the western moraine. Almost all nitrogen entering the Menemsha-Squibnocket Pond Embayment System is transported by freshwater, predominantly groundwater, with the exception of a small fraction of freshwater and nitrogen load that enters the system via three small creeks. Concentrations of total nitrogen and salinity of Atlantic Ocean source waters and throughout the Menemsha-Squibnocket Pond Embayment System were taken from the Water Quality Monitoring Program (a coordinated effort between the Martha's Vineyard Commission and the Coastal Systems Program at SMAST). Measurements of salinity and the distribution of nitrogen and salinity throughout the estuarine waters of the system (2000-2012) were used to calibrate and validate the water quality model (under existing loading conditions).

I.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Menemsha-Squibnocket Pond Embayment System for the Towns of Chilmark and Aquinnah as well as the Wampanoag Tribe. 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.3). 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 Atlantic Ocean (Section IV and VI respectively). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (typically conducted by municipalities) as discussed in Section VI. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of 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 in Section VIII for restoration of the Pond system. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration of the Pond. This latter assessment represents only one of many solutions and is produced to assist the Town in developing a variety of alternative nitrogen management options for this system. Finally, any additional analyses of the Menemsha-Squibnocket Pond Embayment System beyond the standard suite offered by the MEP may be undertaken relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of dredging/breach options to improve nitrogen related water quality. The results of the nitrogen modeling for any additional scenario, should they be undertaken, are typically presented in Section IX.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

Nutrient additions to aquatic systems cause shifts in a series of biological processes that can result in impaired nutrient related habitat quality. Effects include excessive plankton and macrophyte growth, which in turn lead to reduced water clarity, organic matter enrichment of waters and sediments. 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 necessarily a part of the natural evolution of a system.

In most marine and estuarine systems, such as the Menemsha-Squibnocket Pond Embayment System (inclusive of Nashaquitsa and Stonewall Ponds), the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen levels are controlled by source controls or enhanced tidal flushing, then eutrophication is controlled. This approach has been formalized through the development of tools for predicting nitrogen loads from watersheds and the concentrations of water column nitrogen that may result. Additional development of the approach generated specific guidelines as to what is to be considered acceptable water column nitrogen concentrations to achieve desired water quality goals (e.g., see Cape Cod Commission 1991, 1998; Howes et al. 2002).

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

A number of studies relating to nitrogen loading and water quality have been conducted within the Menemsha-Squibnocket Pond Embayment System over the past two decades. Among these studies, several contained information of sufficient quality that it could be used to support the MEP modeling and assessment of this estuary and these are described briefly below.

Nutrient Loading to Menemsha and Squibnocket Ponds (2001, updated 2010): This report was prepared by the Martha's Vineyard Commission and submitted to the Massachusetts Department of Environmental protection (MassDEP) and the US EPA in 2001. The loading study was subsequently up-dated in 2010. Specifically, Mr. William Wilcox (MVC Water Resources Planner at the time of the study) designed the project and served as principal investigator, author, and MVC project quality assurance officer. The study was completed through a contractual arrangement with the University of Massachusetts Cooperative Extension. Additionally, scientists currently from the Coastal Systems Program at the UMASS School for Marine Science and Technology and presently involved with the MEP performed the chemical analyses in support of this 2001 Menemsha-Squibnocket Pond loading study when SMAST was originally the Center for Marine Science & Technology. This study was undertaken to assess the potential impact of residential development in the watersheds of three Vineyard ponds: 1) Chilmark Pond, 2) Menemsha Pond and 3) Squibnocket Pond. The components of the study that were used to make the assessment included: the amount of residential development expected in each watershed, the volume of each pond, its tidal circulation and the desired water quality goal.

As summarized in the report, Menemsha Pond is an important shellfish resource to the Towns of Aquinnah and Chilmark as well as the Wampanoag Tribe of Aquinnah. Herring, returning to spawn in Squibnocket Pond, pass through Menemsha Pond in the spring. Squibnocket Pond is a spawning site for a large herring population and a wildlife and aesthetic resource. The Wampanoag Tribe manages a commercial herring fishery at the inlet to Squibnocket Pond (Herring Creek).

According to the MVC loading assessment, Menemsha Pond appears to be a strongly flushed water body with the capacity to withstand the projected nitrogen loading as determined in 2001. The most intensive land use area, Menemsha Basin, is a seasonal use area situated near the inlet to the pond where nutrient loading is either removed with the ebb tide or diluted with the strong influx of Vineyard Sound water on the flood tide. In the 2001 assessment, management activities in the form of shellfish enhancement programs aimed at increasing the economic benefits to the shellfish industry were identified as potentially having a positive impact on water quality by removing nitrogen and other nutrients from the system. Similarly, dredging done to maintain recreational and commercial boating access and safety was identified as a mechanism for maintaining a strong tidal flow which would flush nutrients from the system. In 2001 and consistent with the 2010 update, the MVC concluded it "made sense to continue with the low density development pattern provided by current zoning" as understanding of nutrient related water quality increased for the overall system. The assessment did recommend that nitrogen removal from wastewater be best focused in areas of higher density in order to take advantage of economies of scale.

Squibnocket Pond was considered a more complex system based on the changing tidal pattern and by the substantial fresh water component of the water column. In 2001 Squibnocket Pond showed some poor water quality symptoms which the MVC concluded "must be attributed primarily to natural eutrophication as the current development pattern is minimal." The MVC did also state, "We can only predict that these symptoms will worsen as the watershed builds out and groundwater brings more nutrients into the pond."

Based on the assessment completed by the MVC, it did recommend that the Town of Aquinnah consider adopting a Squibnocket Pond District similar to that on the Chilmark side as a means to provide guidance or regulation regarding residential nitrogen loading from lawns and septic systems. The 2001 nitrogen loading assessment did go so far as to make recommendations as to how much nitrogen should be allowed to enter the system with recommendations for managing the inputs. As excerpted from the report:

> "The simplest approach to meeting nitrogen loading limits may be to adjust zoning in this District to require a loading limit of 2.33 kilograms per acre on average over the watershed (the loading limit divided by the acreage in the watershed). However, when the existing fixed sources such as acid rain are taken into account, the average loading allowed from residential uses falls to about 0.9 kilograms per acre. We estimate that a year round dwelling produces about 5.3 kilos of nitrogen per year from septic leachate and 1.5 from the lawn for a total of 6.8 kilos. However, when the seasonal dwellings are brought into consideration, the average nitrogen loading per dwelling is 3.45 kilos from septic leachate and 1.5 from lawns or 5 kilos per dwelling. On average at build out, across existing and future dwellings, lot sizes should average 5.4 acres. An alternative might be to require that advanced denitrifying septic systems reduce nitrogen loading on any lots less than 5.4 acres in size. Other short term suggestions include a study of the herring population in the pond to determine if there are steps that can be taken to enhance the size of the run. Similarly, the oyster production from the pond should be managed to produce large quantities of vigorous young oysters which utilize nitrogen. The oysters can then be exported to Menemsha Pond to prepare them for market."

The 2001 MVC loading assessment also indicates that the connection between Squibnocket and Ponds is the weak link regarding the flushing of the pond and recommends that the Herring Creek be surveyed to determine if there are any environmentally safe steps that can be taken to increase the exchange of water between Menemsha Pond and Squibnocket Pond so as to increase the rate of flushing between the two systems. Modification to the Herring Creek should however be undertaken with caution as "any increase in salt water into the system will have ecological and circulation effects which should be evaluated before taking steps to increase the flow through the Herring Creek." The report does indicate that increasing flushing could be a cost effective means to loosen the growth restrictions potentially required to manage nutrient loading in the Menemsha-Squibnocket Pond Embayment System.

Martha's Vineyard Coastal Ponds Water Quality Survey - Summer 2003 (2005): This report was prepared by the Martha's Vineyard Commission and the overall objective of the investigation was to establish existing water quality conditions in a variety of Martha's Vineyard ponds as a baseline for future investigations as well as to meet the three year minimum baseline water quality data requirement for inclusion into the Massachusetts Estuaries Project. Menemsha-Squibnocket Ponds water quality monitoring stations sampled as part of this effort are depicted in Figure II-1a. The 2004 "project" was funded by the Massachusetts 604(b) Grant program continued to build the MVC water quality database for nine coastal ponds, specifically: Menemsha Pond, Squibnocket Pond, Chilmark Pond, Sengekontacket Pond, Farm Pond, Lake Tashmoo, Cape Pogue Pond, Pocha Pond and Lagoon Pond.

As described in the 2005 water quality summary report, Menemsha Pond is one of the most vigorously circulated ponds on Martha's Vineyard and as such the strong tidal flow removes nutrients and results in better water quality. Total Organic Nitrogen, however, did reach undesirable levels in Menemsha Basin and in the Nashaquitsa and Stonewall Ponds stations in 2003. Total Organic Nitrogen values at the stations in more well-circulated areas were very good. Chlorophyll concentration was good at all stations. Inorganic nitrogen was higher at the stations with large sources like wastewater (Menemsha basin) or areas with reduced circulation (near Stonewall Pond). Dissolved oxygen saturation was lower in the deep water but not to levels where impacts on marine organisms would occur. Generally water quality during 2003 was good with some stations varying from average to good. Squibnocket Pond also had elevated Total Organic Nitrogen that ranged between 0.8 and 1.2 ppm. Chlorophyll content was not excessive during the 2003 study period. Dissolved oxygen saturation was acceptable at the times measured, however, a high saturation (120%) implies that the oxygen content may be subject to overnight decline and the report recommended the installation of continuous recording devices to evaluate the possibility of periods of hypoxia/anoxia. Overall, the water quality in the system during 2003 was "somewhat reduced".

MVC/Town of Chilmark/Town of Aquinnah Water Quality Monitoring Program (2000-2012): A significant record of baseline water quality throughout the Menemsha and Squibnocket Pond System has been developed over the past 15 years, in large part due to the efforts by the Martha's Vineyard Commission and the Wampanoag Tribe of Gay Head. The Martha's Vineyard Commission partnered with SMAST-Coastal Systems Program scientists in 1995 to develop and implement a nutrient related water quality monitoring program of the estuaries of Martha's Vineyard, inclusive of Menemsha and Squibnocket Ponds in the Town of Chilmark and Aquinnah. Sample analysis was conducted by the Coastal Systems Analytical Facility at SMAST-UMD. For the Menemsha-Squibnocket Pond Embayment System, as well as the other estuarine systems of Martha's Vineyard, the focus of the water quality monitoring effort has been to gather site-specific data on the current nitrogen related water quality throughout the estuarine reach of a given 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.

The water quality monitoring program was initiated in 1995 and along the way supported by funds obtained from the Massachusetts 604B Grant Program (1999). Throughout the water quality monitoring period, sampling was generally undertaken between 4 and 6 times per summer between the months of June and September. The MVC/Town based Water Quality Monitoring Program for Menemsha and Squibnocket Ponds developed the baseline data from sampling stations distributed throughout the main basin as well as the major tributary coves (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 gathered by the Water Quality Monitoring Program and watershed and embayment data collected by MEP Technical Staff. The MEP effort also builds upon previous watershed delineation and land-use analyses as well as eelgrass surveying by the MassDEP Eelgrass Mapping Program and MEP Technical Staff. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Menemsha-Squibnocket Pond Embayment System. The MEP has incorporated appropriate data from previous studies to enhance the determination of nitrogen thresholds for the Menemsha-Squibnocket Pond Embayment System and to reduce costs of restoration for the Town of Chilmark, Aquinnah and the Tribe.

Wampanoag Tribe Water Quality Monitoring Program (2000-2015): In addition to water quality monitoring that has been undertaken through coordinated efforts with the Martha's Vineyard Commission (MVC), the Wampanoag Tribe of Aquinnah does do regular testing of Menemsha and Squibnocket Ponds water quality throughout the year. The Tribe operates its own analytical facility and has been collecting nutrient related water quality data for a number of years, primarily nitrate, nitrite and ammonia. The tribes program was streamlined in 2008 when it developed a water quality strategy for field assessments. The Tribe's sampling is currently being used to maintain baseline data for the evaluation of temporal and spatial trends in specific nutrient parameters mentioned above with a specific emphasis on issues such as nitrogen loading and storm water runoff. The Tribe does not develop an annual report that summarizes the data collected in a given year and how that compares to all the data the program has taken since its commencement, however, all data collected is submit yearly to EPA in a brief report format. In addition, all of the data is uploaded yearly, to EPA's WQX database, which can be accessed by the public. Station locations that are monitored by the Tribe are depicted in Figure II-1b,c,d.

Regulatory Assessments of Menemsha Pond and Squibnocket Pond Resources: The Menemsha-Squibnocket Pond Embayment System (inclusive of the Nashaquitsa Pond and Stonewall Pond basins) contains a variety of natural resources of value to the citizens of Chilmark, Aquinnah, the Wampanoag Tribe and Martha's Vineyard 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 Menemsha-Squibnocket Pond Embayment System these include:

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

Figure II-1a. MVC/Town of Chilmark/Aquinnah Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the MVC/SMAST and volunteers/staff from the Wampanoag Tribe.

Figure II-1b. Wampanoag Tribe of Aquinnah Water Quality Monitoring Program in Menemsha Pond (perimeter stations). Estuarine water quality monitoring stations sampled and analyzed by staff from the Wampanoag Tribe.

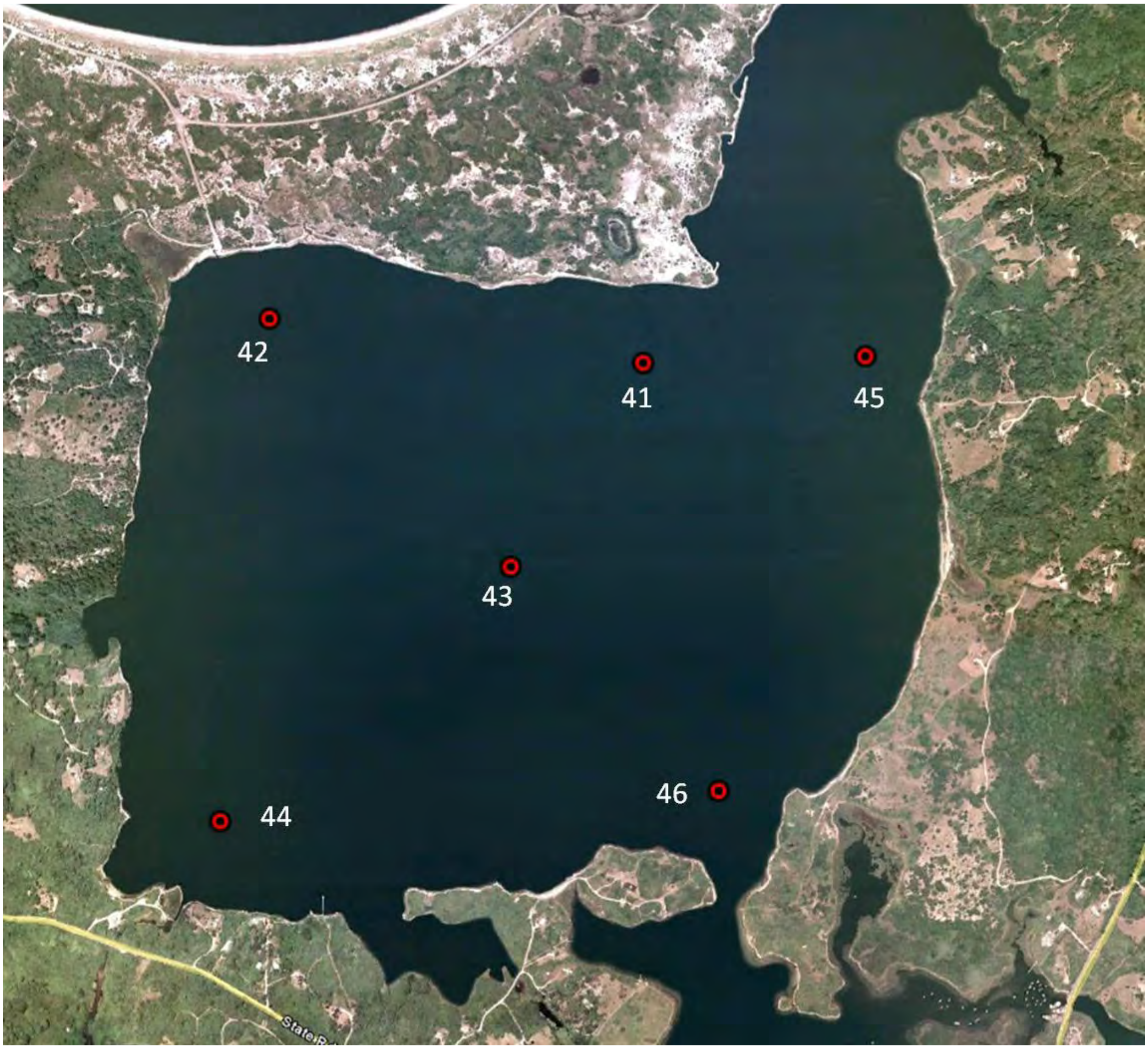

Figure II-1c. Wampanoag Tribe of Aquinnah Water Quality Monitoring Program in Menemsha Pond. Estuarine water quality monitoring stations sampled and analyzed by staff from the Wampanoag Tribe.

Figure II-1d. Wampanoag Tribe of Aquinnah Water Quality Monitoring Program in Squibnocket Pond. Estuarine water quality monitoring stations sampled and analyzed by staff from the Wampanoag Tribe.

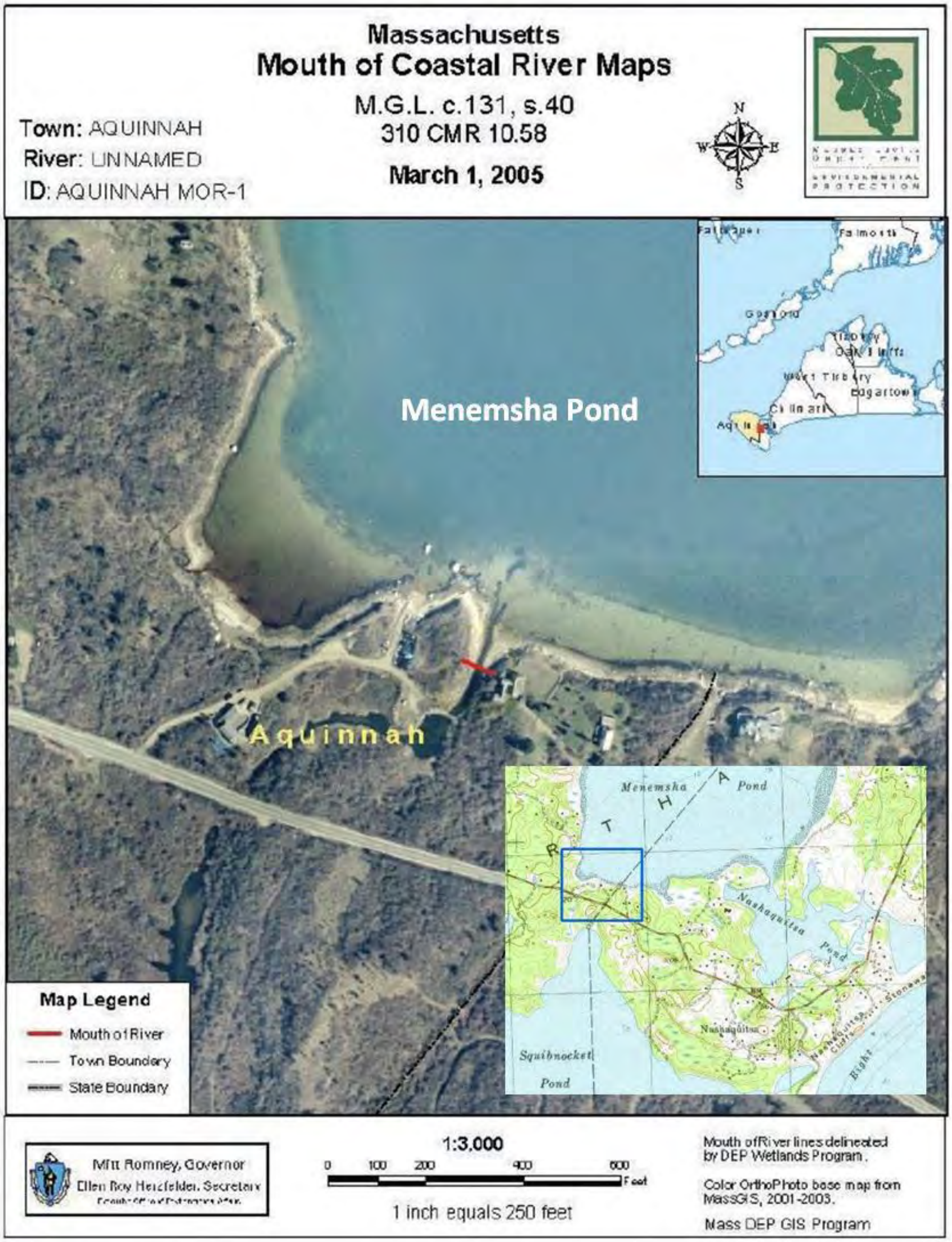

Figure II-2. Regulatory designation for the mouth of “River” under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

Figure II-3a. 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. However, areas dominated by wetlands with persistent fecal coliform levels >14 cfu per 100 mL may be prohibited to shellfishing until the cause of the contamination (frequently wildlife and birds) is documented.

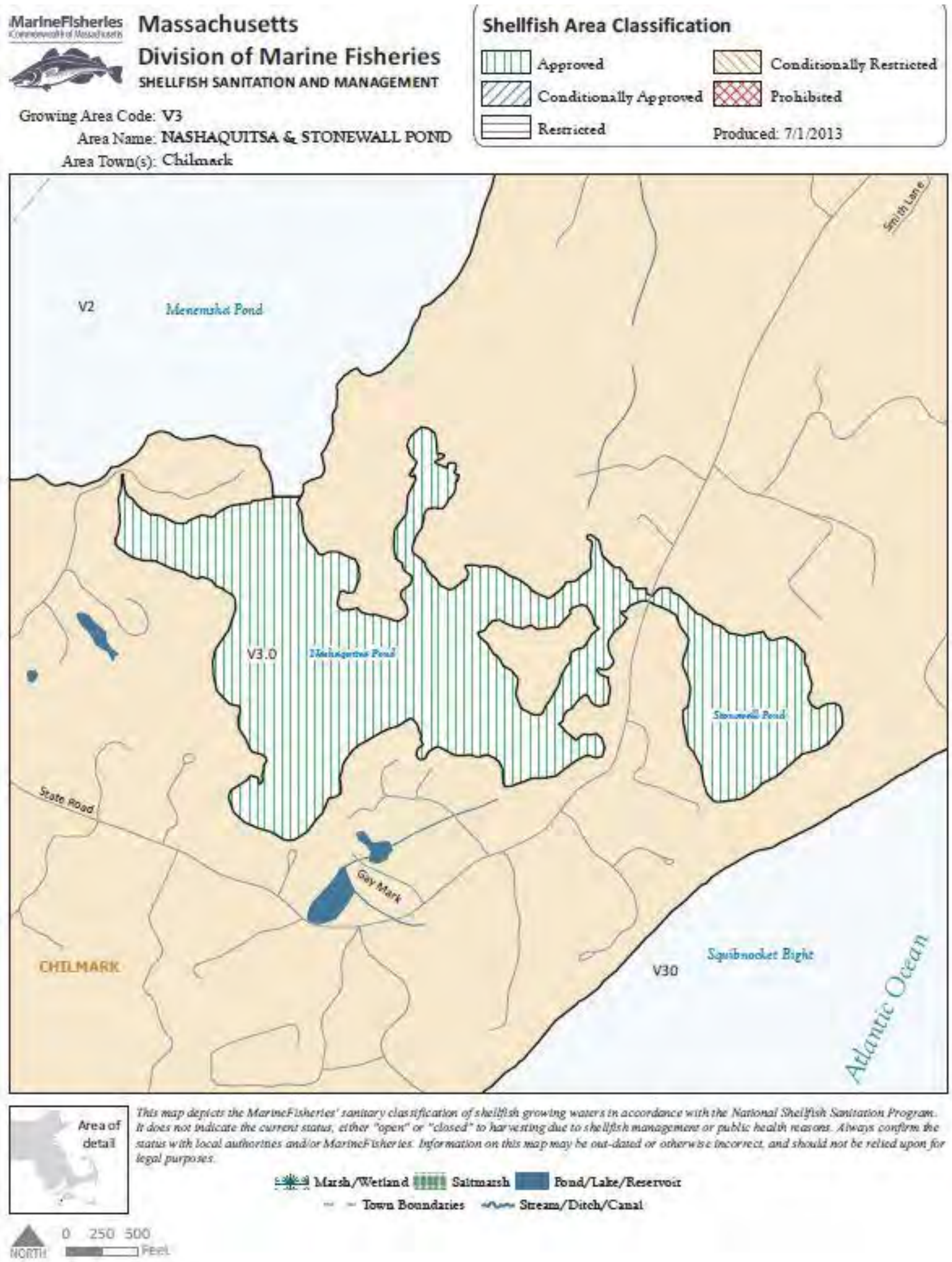

Figure II-3b. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas. However, areas dominated by wetlands with persistent fecal coliform levels >14 cfu per 100 mL may be prohibited to shell fishing until the cause of the contamination (frequently wildlife and birds) is documented.

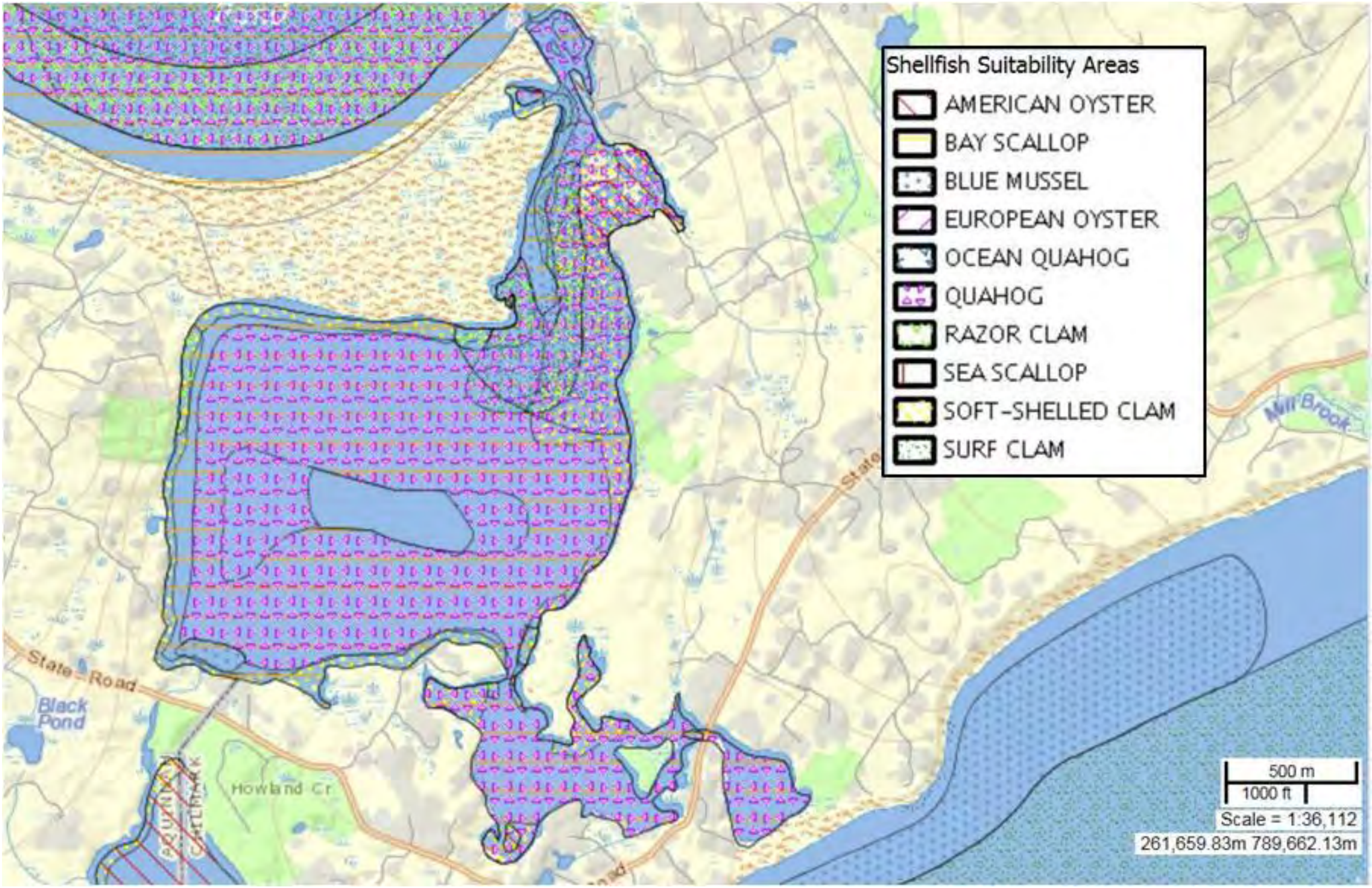

Figure II-4a Location of shellfish suitability areas within the Menemsha Pond Embayment System as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean that a shellfish population is "present" or that harvest is allowed.

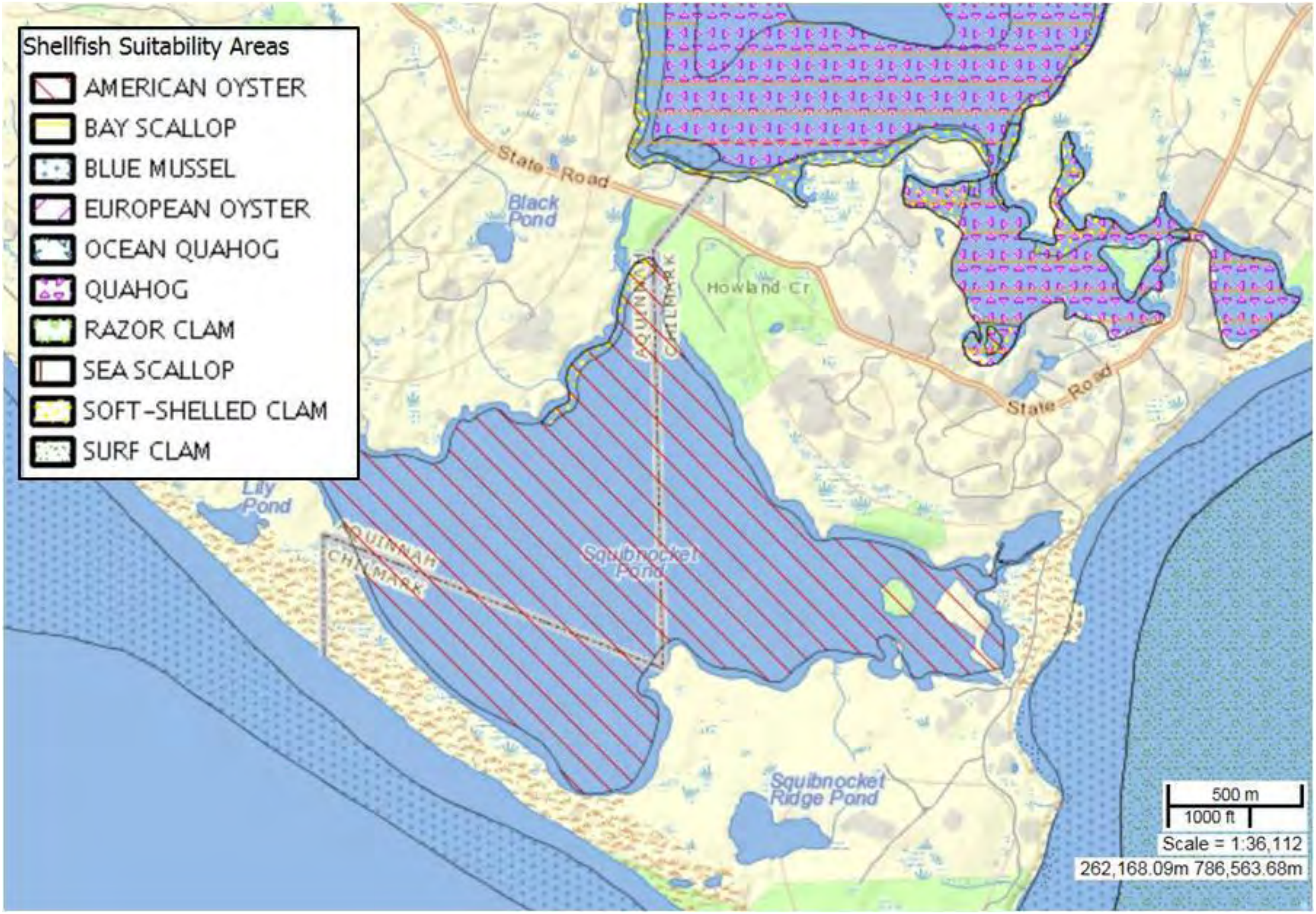

Figure II-4b Location of shellfish suitability areas within the Squibnocket Pond Embayment System as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean that a shellfish population is "present" or that harvest is allowed.

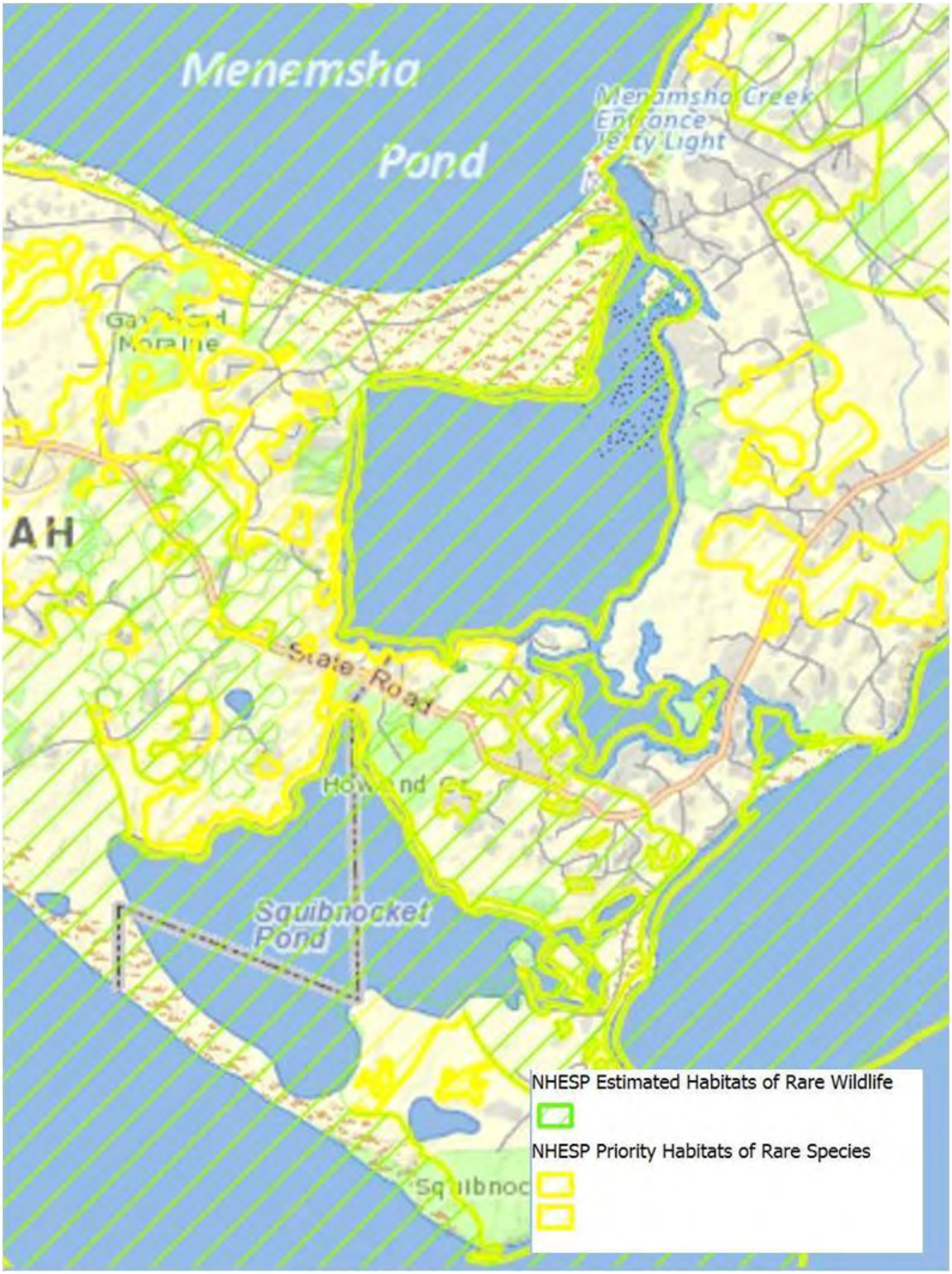

Figure II-5. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Menemsha-Squibnocket Pond Embayment System as determined by the Massachusetts Natural Heritage and Endanger Species Program (NHESP).

Figure II-6. Presence of Anadromous Fish within the Menemsha-Squibnocket Pond Embayment System as determined by the Massachusetts Division of Marine Fisheries (DMF).

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The island of Martha's Vineyard is located along the southern edge of late Wisconsinan glaciation (Oldale and Barlow, 1986). The island was located between the Cape Cod Bay and Buzzards Bay lobes of the Laurentide ice sheet 14 to 16 thousand years ago. As such, the geology of the main portion of the island is largely composed of glacial outwash plain with moraines to the east and west and subsequent reworking of these deposits by the rise in sea levels and ocean currents that has occurred since the retreat of the glaciers. The main portion of the island is composed of outwash plains with layers of sands deposited by glacial meltwaters. The moraines, on the other hand, are areas where the glacial ice lobes moved back and forth with warming and cooling of the climate. These moraines are located along the Nantucket Sound/eastern and Vineyard Sound/western sides of the island. The moraines generally consist of unsorted sand, clay, silt, till, and gravel, but the western moraine has a more complex geology than the eastern moraine. The western moraine is composed of thrust-faulted coastal plain sediments interbedded with clay, till, sand, silt and gravel, while the eastern moraine has more permeable materials overlying poorly sorted clay, silt, and till (Delaney, 1980). The relatively porous deposits that comprise most of the Vineyard outwash plain create a hydrologic environment where watersheds 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). Delaney (1980) and other subsequent characterizations have indicated that these characteristics also apply to the eastern moraine. Groundwater modeling on Martha's Vineyard has largely been confined to these more porous and relatively simple geologic settings.

The Menemsha-Squibnocket Pond Embayment System watershed is located entirely within the western moraine. Characterizations of the western moraine are very limited and are likely to be very site-specific given its complex geologic mix. Regional groundwater contours created for the United States Geological Survey (USGS) regional water table map do not extend into the western moraine and there were only a few wells drilled within the moraine during initial USGS characterizations (Delaney, 1980). The study grid for the regional MODFLOW groundwater model of the Island originally developed by Whitman and Howard (1994) and updated by EarthTech, Inc. is tilted to avoid the western moraine and includes a no-flow boundary at the western/moraine edge of the model grid. Previous watershed delineations within the western moraine have generally been based on surface topography, which would be consistent with soils that create more runoff than infiltration. The MEP watershed to Chilmark Pond was based on both groundwater contours and surface topography since the eastern edge of the watershed is located within the outwash plain and the western edge was in the western moraine (Howes, *et al.*, 2013). The Chilmark Pond watershed forms the eastern boundary of the Menemsha-Squibnocket Pond Embayment System watershed. Through the MEP, project staff had the chance to re-review previous delineations, use the MEP streamflow data to evaluate delineations, and update the estuary watersheds to include internal stream and pond basin subwatersheds.

III.2 MENEMSHA POND - SQUIBNOCKET POND CONTRIBUTORY AREAS

The overall MEP Menemsha-Squibnocket Pond Embayment System watershed is situated in the western portion of Martha's Vineyard, is bounded by the Atlantic Ocean to the south and is divided between the Towns of Chilmark and Aquinnah (Figure III-1). The Menemsha-Squibnocket Pond Embayment System watershed and subwatershed delineations are based on: 1) USGS topographic maps in the western moraine, 2) MEP streamflows, 3) MassDEP wetland

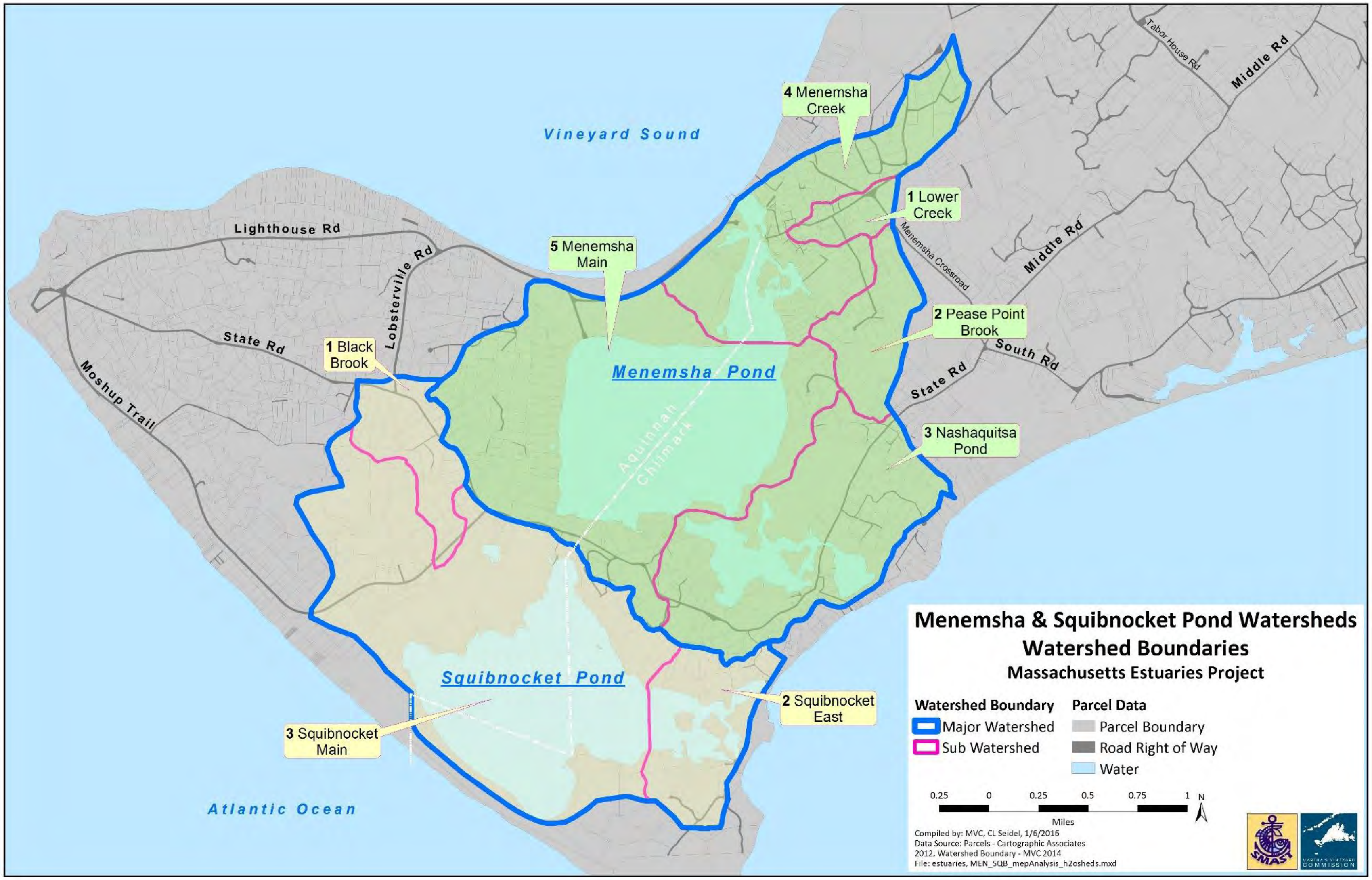

Figure III-1. Watersheds and subwatershed delineations for the Menemsha-Squibnocket Pond Embayment System. Sub-watersheds are delineated to MEP stream gauges and sub-units within the water quality models (see Section IV and Section VI, respectfully). The watersheds are divided between the Towns of Chilmark and Aquinnah.

characterizations (MassDEP, 2009), 4) groundwater elevations where available in the sandy outwash aquifer areas and 5) best professional judgment. The outer boundary of the Menemsha-Squibnocket Pond Embayment System watershed is based on the MVC delineation, which was created based on topographic inspection. This approach focuses on determining the pattern of local maximum elevations in US Geological Survey 1:25,000 topographic quadrangle maps. Watershed divides are based upon the tendency of surface water (and underlying groundwater) to flow downhill perpendicular to the topographic contour lines from these maximums. Divides drawn upon topographic maps can be confirmed by observing general patterns of surface water flow during rainfall or by measuring the flow of water in streams over a hydrologic cycle as was done by the MEP for this investigation. The eastern edge of the Menemsha-Squibnocket Pond Embayment System watershed abuts the Chilmark Pond watershed, which was largely confirmed through MEP stream monitoring over the 2005-2007 hydrologic years, as well as water quality measurements within the pond (Howes, *et al.*, 2013).

In order to develop the interior stream subwatersheds for the Menemsha-Squibnocket Pond Embayment System watershed, MEP staff initially delineated topographic watersheds with assistance from the MVC staff. The areas of these watersheds were then combined with the island-specific recharge rate of 28.7 inches/year to produce estimated average watershed flows. This information was then compared to measured MEP streamflows developed over the 2006-2007 hydrologic year (see Section IV.2). This comparison produced a reasonable match between estimated and measured flows.

The island-specific annual recharge rate is largely based on review of the relationship between recharge and precipitation rates used in regional Cape Cod groundwater modeling (Walter and Whealan, 2005). The USGS used a recharge rate of 27.25 in/yr for calibration of Cape Cod groundwater models to match measured groundwater levels and available streamflow measurements. The Cape Cod recharge rate is 61% of the estimated average 44.5 in/yr of precipitation on the Cape. Precipitation data collected by the National Weather Service at Edgartown on Martha's Vineyard 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 has been used for all MEP reports on Martha's Vineyard and was developed in consultation with MVC staff.

The MEP watershed areas to Menemsha Pond and Squibnocket Pond portions of the overall systems are 1,877 acres and 1,094 acres, respectively (Table III-1). Available previous reports discuss watershed areas to the Menemsha-Squibnocket Pond Embayment System, but maps of these areas were very limited. Gaines and Broadus (1990) estimated a Squibnocket Pond watershed area of 5.41 sq. km. (1,337 acres). Wilcox (2001) reported a Squibnocket Pond watershed area of 1,303 acres and a Menemsha Pond watershed area of 1,856 acres. Wilcox (2001) delineations showed that the primary difference in the Wilcox (2001) Squibnocket watershed area with the current MEP delineation is the inclusion of a wetland area in the north portion of the western lobe (Figure III-2) Review of MEP streamflow measurements in Black Brook showed that this area should be included in the Menemsha Main subwatershed; inclusion of this area in the Black Brook watershed would have caused watershed flows to significantly exceed MEP streamflow measurements (see Section IV.2). MEP confirming streamflow measurements provide a reasonable check on watershed delineations. The MEP watershed delineation for the Menemsha-Squibnocket Pond Embayment System also provide updates on previous delineations by including eight subwatershed delineations to the streams and various portions of the combined system.

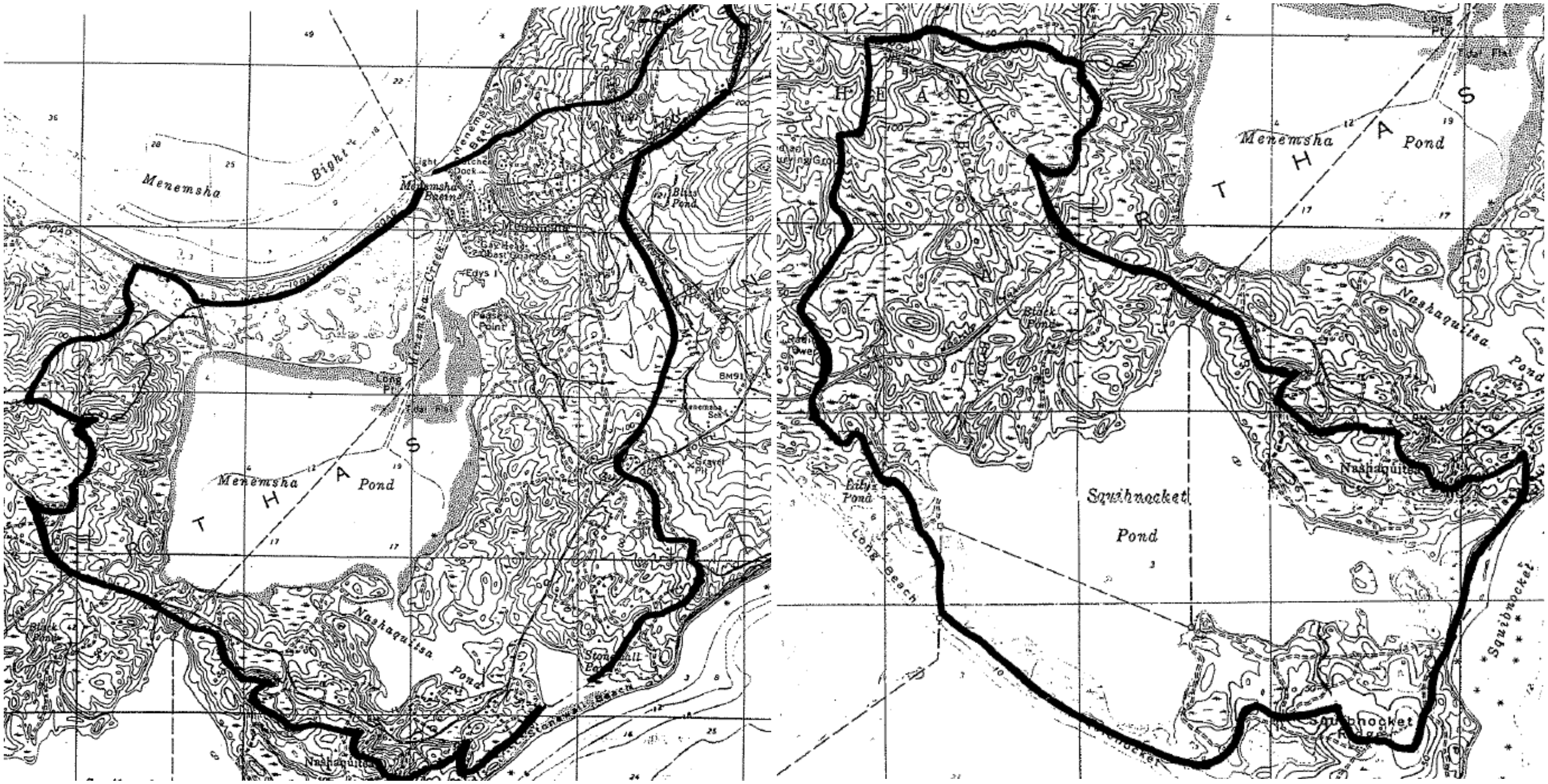

Figure III-2. Previous watershed delineations of Menemsha Pond and Squibnocket Pond. Delineations are from Wilcox (2001). Most significant differences from the MEP watersheds are assignment of wetland area in western Menemsha Pond subwatershed to Squibnocket Pond subwatershed and the location of the eastern watershed boundary for Menemsha Pond. MEP assignment of wetland area to the Menemsha Pond watershed is based on balancing of delineations with measured readings within the Black Brook subwatershed (see Section IV.2), while eastern watershed boundary for Menemsha Pond is based on MEP Chilmark Pond watershed boundary, which is also balanced with measured streamflows (Howes, *et al.*, 2013).

Based on the review of the available data, MEP Technical Team staff is confident that the delineations in Figure III-1 are accurate and an appropriate basis for completion of the linked watershed-embayment model for the Menemsha-Squibnocket Pond Embayment System. Figure III-1 shows the overall Menemsha-Squibnocket Pond Embayment System MEP watershed and the eight subwatersheds, including watersheds to Black Brook, Pease Point Brook, Lower Creek and Nashaquitsa Pond. The watershed areas and the island-specific recharge rate were also used to estimate direct groundwater flow to the Menemsha-Squibnocket Pond Embayment System (see Table III-1). The subwatershed discharge volumes and measured streamflow volumes were used to assist in the salinity calibration of the water quality model. The overall estimated groundwater flow into the Menemsha-Squibnocket Pond Embayment System from the MEP delineated watersheds are 15,237 m3/d and 8,840 m3/d, respectively.

Table III-1. Daily groundwater discharge from each of the sub-watersheds to the Menemsha-Squibnocket Pond Embayment System.

Watershed	Shed #	Watershed Area (acres)	Discharge	
			m^3/day	ft^3/day
Menemsha Pond				
Lower Creek	1	69	555	19,596
Pease Point Brook	2	171	1,382	48,816
Nashaquitsa Pond	3	538	4,341	153,310
Menemsha Creek	4	422	3,477	122,787
Menemsha Main	5	677	5,482	193,595
Menemsha Pond TOTAL		1,877	15,237	538,104
Squibnocket Pond				
Black Brook	1	175	1,416	50,001
Squibnocket East	2	191	1,545	54,547
Squibnocket Main	3	727	5,879	207,621
Squibnocket Pond TOTAL		1,094	8,840	312,168

NOTES:

a) Discharge rates are based on 28.7 inches per year of recharge, which is based on average precipitation recorded at Edgartown over the past 20 years.

b) Watershed areas include only land area and exclude estuary surfaces.

Review of watershed delineations for the Menemsha-Squibnocket Pond Embayment System allows new hydrologic data to be reviewed/incorporated as appropriate 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 Menemsha-Squibnocket Pond Embayment System.

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

Management of nutrient related water quality and habitat health in coastal waters requires determination of the amount of nitrogen transported by freshwaters (surface water flow, groundwater flow) from the surrounding watershed to the receiving embayment of interest. In southeastern Massachusetts and the Islands (Martha's Vineyard and Nantucket), the nutrient of management concern for estuarine systems is nitrogen and this is true for the Menemsha Pond and Squibnocket Pond Embayment System. Determination of watershed nitrogen inputs to this embayment system requires: (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 coordinated the development of the watershed nitrogen loading for the Menemsha Pond-Squibnocket Pond Embayment System with the Martha’s Vineyard Commission (MVC) staff. This effort led to the development of nitrogen-loading rates (Section IV.1) to the Menemsha Pond and Squibnocket Pond sub-watersheds (Section III). The watersheds to Menemsha Pond and Squibnocket Pond were sub-divided into five (5) and three (3) subwatersheds, respectively. These subwatersheds include two streams flowing into Menemsha Pond (Lower Creek and Pease Point Brook) and one stream flowing into Squibnocket Pond (Black Brook). Collectively, all the subwatersheds define the contributing areas/watersheds to the overall Menemsha Pond-Squibnocket Pond Embayment System.

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 approach (Howes, *et al.*, 2001) uses a land-use Nitrogen Loading Sub-Model based upon subwatershed-specific land uses and pre-determined nitrogen loading rates. For the Menemsha Pond-Squibnocket 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. 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 fresh 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 Menemsha Pond and Squibnocket Pond watersheds, there are delineated sub-watersheds to three streams (Lower Creek, Pease Point Brook, and Black Brook). There are no freshwater ponds with delineated watersheds within the combined Menemsha-Squibnocket Ponds watershed. Surface water attenuation in the streams is discussed in Section IV.2. Other, smaller aquatic features within the watersheds to Menemsha Pond and Squibnocket Pond do not have separate watersheds delineated, thus attenuation in these features is 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 (~5-10%) overestimated given the distribution of nitrogen sources, the locations of the gauges, and the locations of 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 streams. Internal nitrogen recycling was also determined throughout the tidal reaches of the Menemsha Pond and Squibnocket Pond Embayments; 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 MEP staff, combined digital parcel and tax assessors' data for the Towns of Chilmark and Aquinnah from the MVC Geographic Information Systems Department. Digital parcels and land use/assessors data are from 2012. These land use databases contain traditional information regarding land use classifications (*e.g.*, MADOR, 2015) plus additional information developed by the MVC.

Figure IV-1 shows the land uses within the Menemsha Pond and Squibnocket Pond watersheds. Land uses in the study area are grouped into six land use categories: 1) residential, 2) commercial, 3) recreational/Chapter 61B, 4) undeveloped (including residential open space), 5) public service/government, including road rights-of-way, and 6) unknown/unclassified. Unknown/unclassified are properties that do not have an assigned land use code in a town assessor's database. These six land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2015). "Public service" in the MADOR system is tax-exempt properties, including lands owned by town or state government (*e.g.*, open space, roads, state forest) and private groups like churches and colleges.

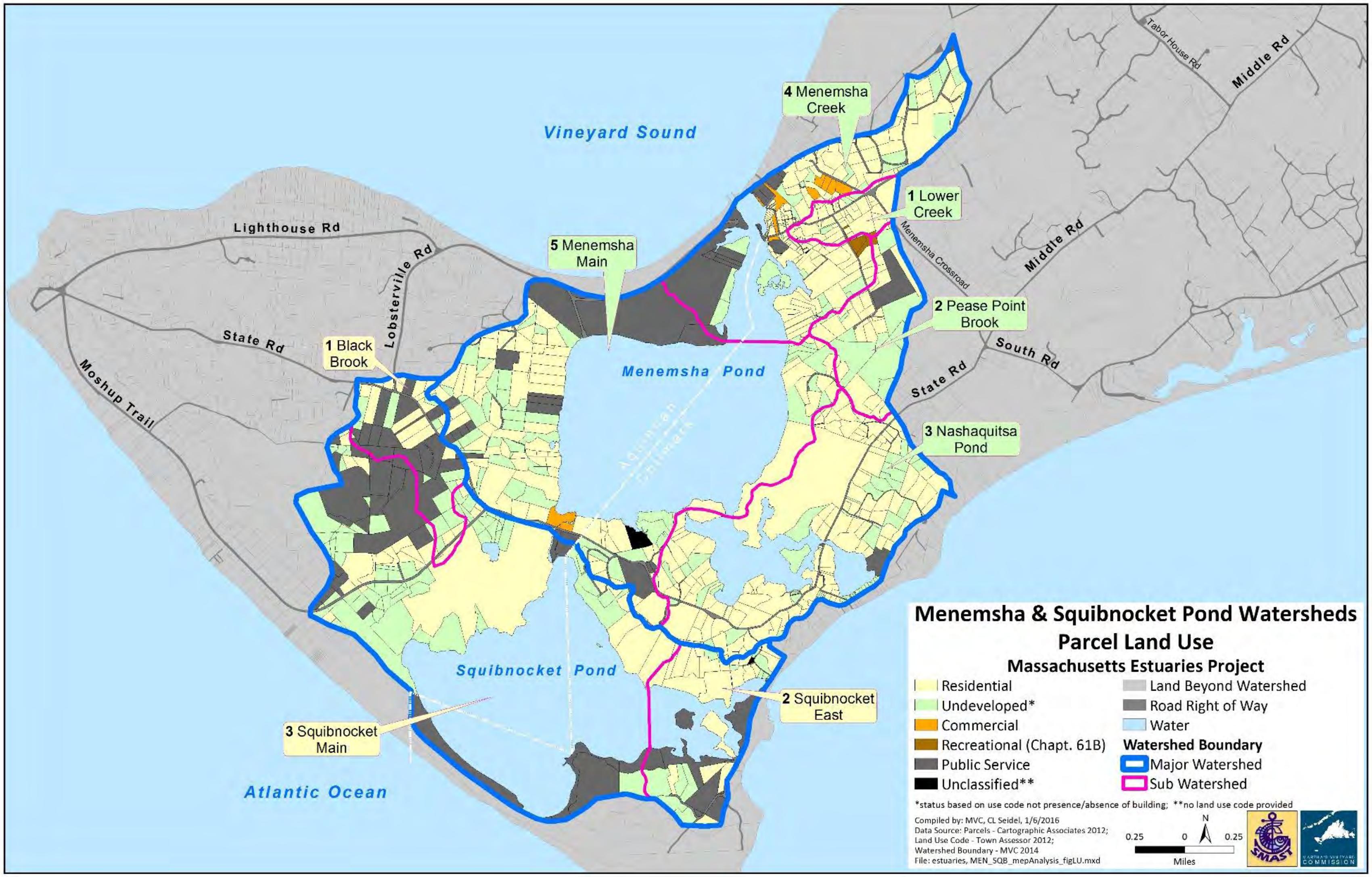

Figure IV-1. Land uses in the Menemsha Pond-Squibnocket Pond Embayment System watershed. The watershed includes portions of the Town of Chilmark and the Town of Aquinnah. Land uses are based on 2012 town assessors' classifications and general categories in MassDOR (2015).

The land use mosaics in the sub-watersheds to Menemsha and Squibnocket Ponds are different. In the overall Menemsha Pond watershed, residential parcels are the predominant land use based on area (60% of the watershed area) (Figure IV-2), while the Squibnocket Pond watershed is somewhat evenly split among residential, public use, and undeveloped areas (38%, 34%, and 28%, respectively, Figure IV-3). These relationships are sustained when the parcel counts are reviewed. Within the Menemsha Pond watershed, 64% of the parcels are residential parcels, 26% are undeveloped, 6% are public service, and the remaining 4% is divided among the other four land use categories. In the Squibnocket Pond watershed, 42% of the parcels are undeveloped, 34% are residential parcels, 23% are public service, and the remaining 1% is unclassified. Amongst the residential parcels, single-family residences (MADOR land use code 101) are the predominant land use both in terms of area and parcel count in both watersheds. Within the Menemsha Pond watershed, single-family residences are 62% of the residential land use area and 81% of the residential parcels. Within the Squibnocket Pond watershed, single-family residences are 51% of the residential land use area and 88% of the residential parcels.

In all the Menemsha Pond subwatershed groupings shown in Figure IV-2, residential parcels are the predominant land use type in all subwatersheds except for Pease Point Brook. Residential parcels range between 43% and 85% of the subwatershed areas. In the Pease Point Brook subwatershed, residential land uses are 43% of the subwatershed area, while undeveloped parcels are 45% of the subwatershed area. In contrast, in the Lower Creek subwatershed, 85% of the subwatershed area is residential land uses. In each of the subwatershed parcel counts, residential parcels are the predominant land use with a range of 55% to 81% of the parcels in the five subwatersheds. Single family residences are the predominant land use amongst residential land uses, accounting for 53% to 76% of the residential areas and 76% to 88% of the parcel counts amongst the subwatersheds.

In all the Squibnocket Pond subwatershed groupings shown in Figure IV-3, residential parcels are the predominant land use type in all subwatersheds except for Black Brook. Residential parcels are 29%, 48%, and 37% of the Black Brook, Squibnocket East and Squibnocket Main subwatersheds. In the Black Brook subwatershed, public service land uses have the most area; occupying 50% of the subwatershed area. These relationships are similar when reviewing parcels within the subwatershed areas. Residential parcels are the most common parcel type in the Black Brook and Squibnocket East subwatersheds (42% and 55% of the respective parcel counts), while undeveloped parcels are 55% of the parcel counts in the Squibnocket Main subwatershed.

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, *et al.*, 2001, 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}.

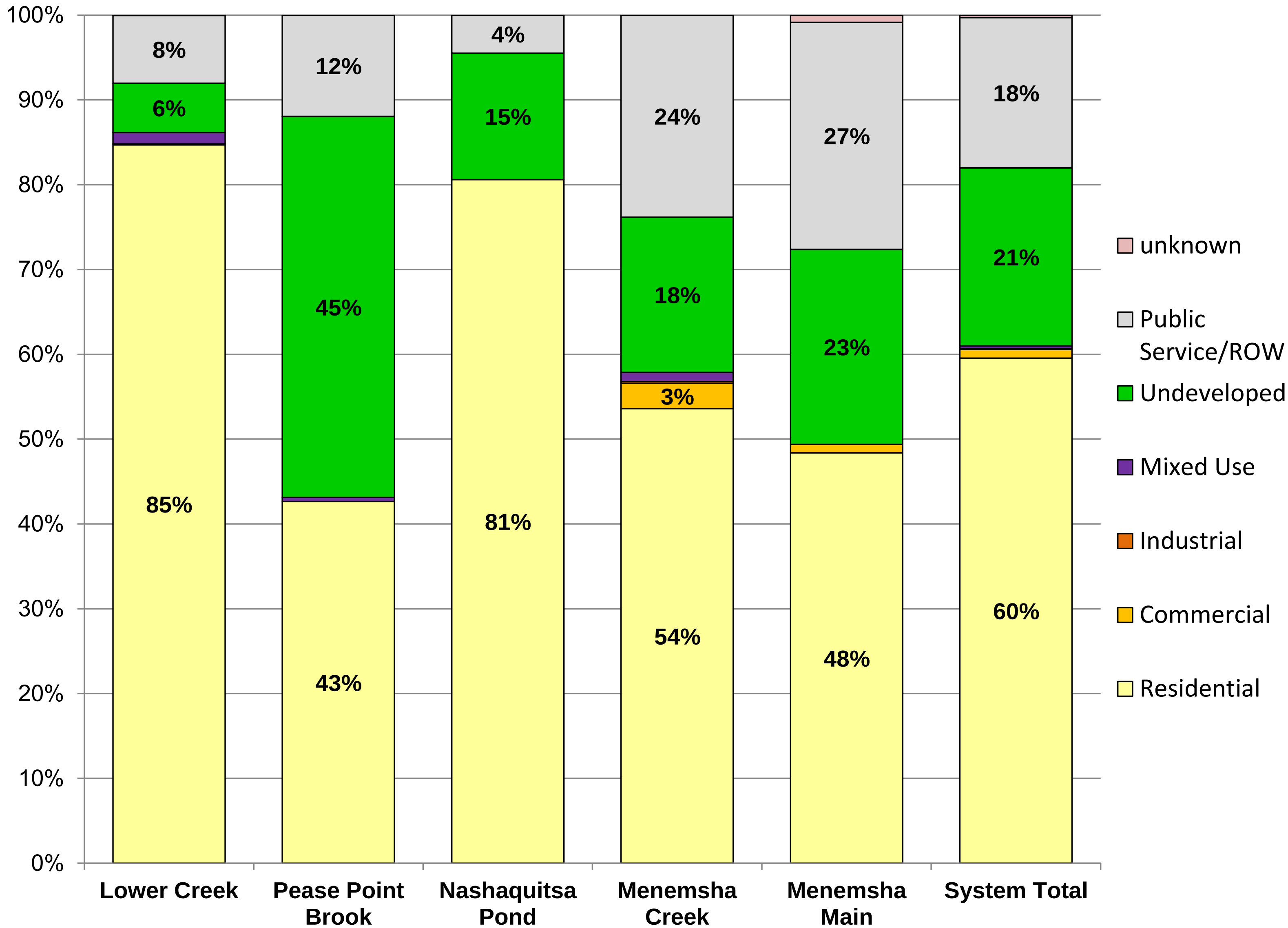

Figure IV-2. Distribution of land-uses by area within the subwatersheds and whole watershed to Menemsha Pond. Only percentages greater than or equal to 3% are shown. Land use categories are based on town and Massachusetts DOR (2012) classifications.

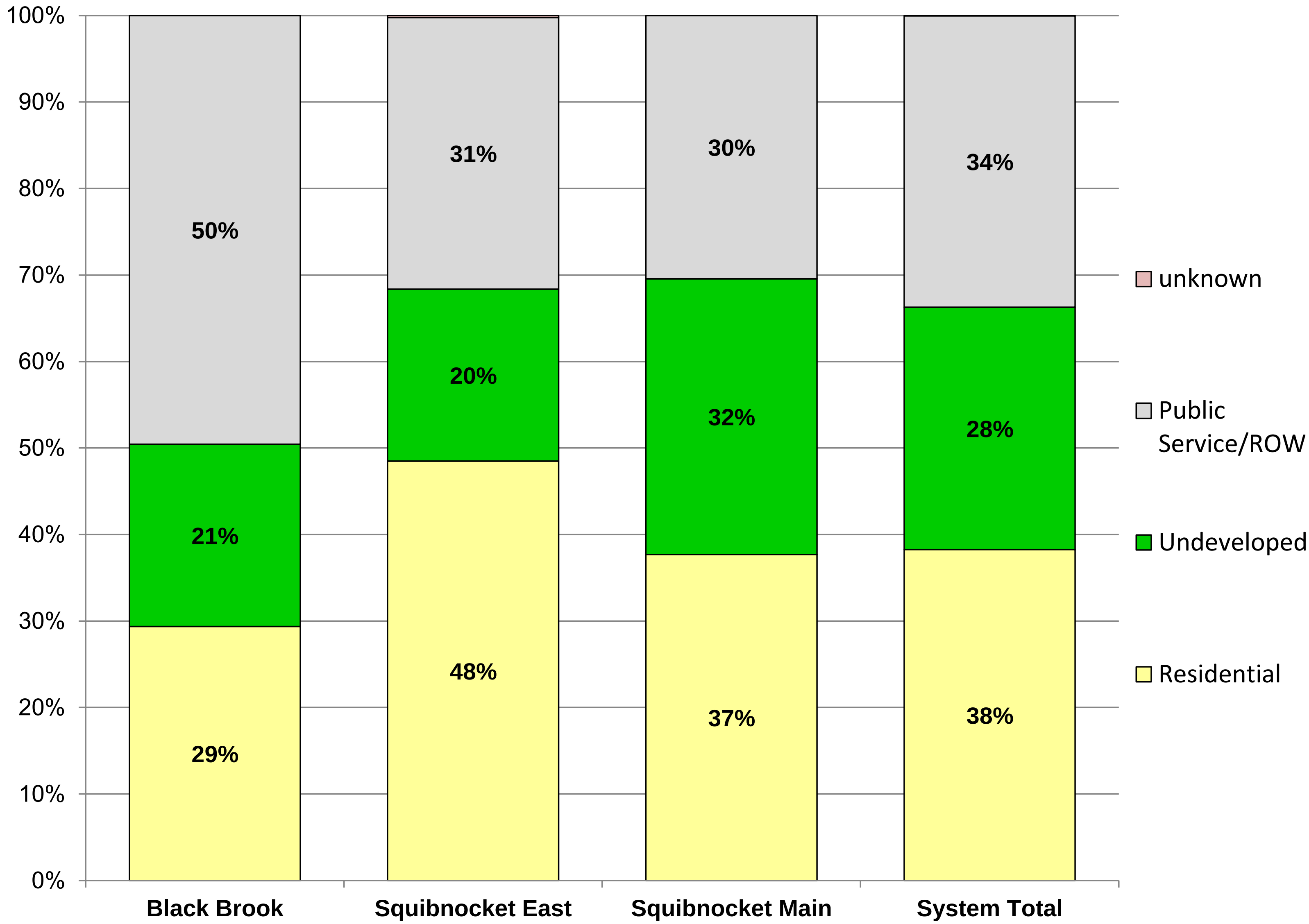

Figure IV-3. Distribution of land-uses by area within the subwatersheds and whole watershed to Squibnocket Pond. Only percentages greater than or equal to 3% are shown. Land use categories are based on town and Massachusetts DOR (2012) classifications.

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts and the Islands, 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 form town-wide occupancy rates. These analyses provide additional support for the use of the water use approach in the MEP study region.

Overall, the MEP water use approach for determining septic system nitrogen loads has been both calibrated and validated in a variety of watershed settings. The approach: (a) is consistent with a suite of studies on *per capita* nitrogen loads from septic systems in sandy 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 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. In the Menemsha Pond and Squibnocket Pond watersheds, this type of water use information was limited; 77 public water connections had data available (2010-2012 water use) with an average parcel water use of 202 gallons per day (range of 183 gpd to 239 gpd). MEP staff then reviewed US Census results to see if this is a reasonable basis for water use within the Menemsha Pond and Squibnocket Pond watersheds. Water use is used as a proxy for wastewater generation from septic systems on all developed properties in the 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).

The Towns of Chilmark and Aquinnah share the watersheds to Menemsha Pond and Squibnocket Pond. Both towns had a large portion of their housing units used as seasonal dwellings. In the 2010 US Census, 74% of the units in the Town of Chilmark were classified as seasonal dwellings, while 69% of the units in the Town of Aquinnah were seasonal. These percentages are only slightly higher than seen in the 2000 US Census where 71% and 67% were classified as seasonal units, respectively. 2010 US Census average occupancy of year-round housing units in both towns was similar: 2.18 people per unit in Chilmark and 2.14 people per unit in Aquinnah. Both towns had an occupancy decrease from the 2000 US Census; Chilmark had a slight drop from 2.21 people per unit, while Aquinnah had a more substantial decrease from 2.44 people per unit. 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 the 2010 average occupancy within Chilmark and 55 gpd per person, average water use would be 120 gpd, while in Aquinnah it would be 118 gpd.

Given that such a high percentage of Chilmark and Aquinnah housing units are occupied only on a seasonal basis, estimates of water use based on US Census data must include an adjustment for the seasonal population increase. Estimates of summer populations on Cape Cod and the Islands derived from a number of approaches (*e.g.*, traffic counts, garbage generation, and WWTF flows) generally suggest average summer population increases from two to three times the year-round residential populations measured during the US Census. The Aquinnah Community Development Plan estimated that average occupancy during the summer is 4.77 people per seasonal unit (MVC, 2004), while the draft FY2015 Chilmark Community Development Strategy lists a summer population increase 4.56 times the year-round population. If it is conservatively assumed that seasonally-classified residential properties in Chilmark and Aquinnah are occupied at four times the 2010 year-round occupancy for three months, the estimated parcel water uses would be 186 gpd and 179 gpd, respectively, while a 5X multiplier would result in flows of 208 and 199 gpd, respectively. Given that the range of measured annual water use averages ranged from 183 gpd to 239 gpd, is corroborated from the analysis of US Census data and town occupancy factors, this supports the use of water use as a reasonable basis of estimating wastewater generation within the Menemsha Pond and Squibnocket Pond watersheds.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilizers, including fertilized lawns, agricultural land uses (including cranberry bogs), and golf courses. Among these, residential lawns are usually the predominant watershed source within this category. In order to add all of these sources to the nitrogen-loading model for the Menemsha Pond-Squibnocket Pond Embayment System, project staff reviewed available information about residential lawn fertilizing practices within other estuary watersheds on Martha's Vineyard and agricultural fertilizer usage. There are no golf courses or cranberry bogs within the Menemsha Pond and Squibnocket Pond sub-watersheds.

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 unless site-specific or watershed-specific data is available. Subsequent assessments have generally confirmed these factors as reasonable (Horsley Witten Group, 2009; Howes and White, 2005).

In order to complete the Menemsha Pond and Squibnocket Pond watershed nitrogen loadings, project staff utilized a standard residential lawn area based on previous assessments completed by MVC and MEP staff. During the preparation of the Tisbury Great Pond MEP assessment (Howes, *et al.*, 2013a), MVC staff measured hundreds of lawn areas in different subwatersheds and found that residential lawn areas averaged approximately 6,100 square feet in the western portions of the watershed. Further review with MEP staff confirmed this and a more limited review completed by MEP staff found that this was also a reasonable lawn area within the Chilmark Pond watershed (Howes, *et al.*, 2013b). MEP staff reviewed lawn areas for random parcels within the Menemsha Pond and Squibnocket Pond watershed and found that 6,100 square feet also seemed to be a reasonable estimate for lawn areas within this overall watershed as well. Other lawn loading factors in the Menemsha Pond and Squibnocket Pond model are those generally used in MEP nitrogen loading calculations.

Nitrogen Loading Input Factors: Agricultural Areas

Working with MEP staff, MVC staff also reviewed all parcels classified as agricultural (700s MADOR land use codes), as well as farms on other non-farm coded properties, and determined the area of fertilized crops and obtained counts for farm animals. Nitrogen application rates and leaching rates are based on standard MEP agricultural crop and farm animal loading factors that have been developed for use in other MEP analyses on Martha's Vineyard. According to this review, neither of the Squibnocket Pond or Menemsha Pond watersheds have noticeable agricultural fields. MVC staff also provided farm animal counts within the watershed (personal communication, Sheri Caseau, MVC, 8/15). This review identified only a few animals within the Menemsha Main subwatershed contributing minimal annual nitrogen loading (6 kg/yr).

Nitrogen Loading Input Factors: Town of Aquinnah Landfill

MEP staff reviewed MassDEP's solid waste database and identified one solid waste site in the Squibnocket Pond sub-watershed: the Town of Aquinnah Landfill. The Town landfill is located off of State Road within the Black Brook subwatershed (Squibnocket Pond subwatershed #1). According to MassDEP records, the landfill is 1.3 acres, unlined, and capped. Water quality monitoring and water level data are collected twice a year from three wells located around the combined site. MEP staff obtained water quality monitoring data from 10 compliance sampling rounds (November 2008 through May 2013) for the landfill (personal communication, Mark Dakers, MassDEP, 1/14). Using this available monitoring information, MEP staff developed a nitrogen load for the landfill site.

MEP staff reviewed the chemical data, well construction details, depths, and locations to determine nitrogen loads for the landfill. Groundwater monitoring data includes nitrate-nitrogen, alkalinity, chloride, and other inorganic and organic measures, but does not include total nitrogen measurements or other components of total nitrogen, such as 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; $r^2 = 0.82$). This relationship was used to estimate ammonium-nitrogen concentrations from the alkalinity data and these estimates were combined with reported nitrate-nitrogen data to provide an estimate of total nitrogen for each sampling run. 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).

Review of the 10 available sampling runs showed that average alkalinity readings seemed to indicate increasing impact toward the south; highest average at GH-103 well located south of the landfill and lowest at the northernmost well (GH-101). MEP staff utilized these alkalinity readings to develop estimated total nitrogen concentrations (estimated ammonium-nitrogen + measured nitrate-N) and subtracted the “upgradient” concentration at GH-101 from the “downgradient” concentration at GH-103 to develop an average TN concentration of 1.97 mg/L from the landfill. Using this concentration, the area of solid waste, and the MEP recharge rate for the area, MEP staff developed an estimated annual total nitrogen load of 7.6 kg from the Aquinnah landfill.

It is acknowledged that this approach for estimating a nitrogen load from the Aquinnah landfill includes a number of assumptions, but it is appropriate based on the available data. A detailed assessment of all the available data is beyond the scope of the MEP, but staff balanced reasonable estimates of the various factors based on the general MEP guidance from MassDEP to include conservatism in nitrogen loading estimates when uncertainty exists in the data. A more refined evaluation and assessment of the established landfill monitoring well network, including, at a minimum, analysis of total nitrogen concentrations, would help to refine this assessment and future management options. However, the nitrogen load from the landfill and other sources within the watershed to Black Brook is included in the direct measurement of nitrogen load transported to the gauge site in the lower reach of the Brook. As a result, uncertainty about the landfill nitrogen source does not have any effect on the total watershed nitrogen load to Squibnocket Pond used in the water quality modeling (Chapter VI).

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 collected in Edgartown since 1947 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, *et al.*, 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 Menemsha Pond-Squibnocket Pond Embayment watershed are summarized in Table IV-1.

Table IV-1. Primary Nitrogen Loading Factors used in the Menemsha Pond and Squibnocket Pond MEP analyses. General factors are from MEP modeling evaluation (Howes, *et al.*, 2001). Site-specific factors are derived from watershed-specific data.

Nitrogen Concentrations:	mg/l	Recharge Rates:[2]	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:[3]	
Natural Area Recharge	0.072	Existing developed parcels and future projected additional residential parcels	202 gpd
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (sq ft)[1]	6,100	Buildout: no commercial, industrial or government/nonprofit additions projected	
Residential Watershed Nitrogen Rate (lbs/1,000 sq ft)[1]	1.08	Building footprint areas (combined watershed average)	2,221 sq ft
Nitrogen leaching rate	20%	Road areas based on MassDOT road GIS coverage	
Farm Animals[4]	kg/yr /animal		
Goat	7.3		
Animal N leaching rate	40%		

Notes:
1) Extensive MEP and MVC staff measurements of lawn areas in both Tisbury Great Pond and Chilmark Pond watersheds and limited measurements within the Menemsha Pond and Squibnocket Pond watersheds show this is a reasonable average estimate of lawn area.
2) Based on precipitation rate of 46.9 inches per year (20 year average at long-term Edgartown station); recharge is based on recharge to precipitation relationship used in Cape Cod groundwater modeling (Walter and Whealan, 2005).
3) Average water use is based on available public water connections within the combined watersheds. Water use estimates based on US Census population counts suggest this is a reasonable average for the towns in the watershed.
4) Crop and farm animal loading rates and leaching rates are standard MEP factors based on available literature and USDA guidance. Only animals with specific-counts on individual parcels.

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, nitrogen loads from parcels were assigned to various watersheds based initially on whether nitrogen load source areas were located within a respective watershed. This review of individual parcels straddling watershed boundaries included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Individualized information for parcels with atypical nitrogen loading (farm animals, landfills, 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 Menemsha Pond and Squibnocket Pond estuaries. 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 to subwatersheds, all relevant nitrogen loading data were assigned by subwatershed. This step includes summarizing water use, parcel area, frequency, private wells, and road area. Individual sub-watershed information was then integrated to create Menemsha Pond and Squibnocket Pond Watershed Nitrogen Loading modules 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 Menemsha Pond and Squibnocket Pond systems, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), fertilizer (including residential lawns), impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the Menemsha Pond and Squibnocket Pond watershed nitrogen-loading models are the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figures IV-2, IV-3 and Figure IV-4a,b, respectively). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport through streams or ponds. These attenuated loads reach the estuarine system and are used in the embayment water quality sub-model. Natural nitrogen attenuation in the Menemsha Pond and Squibnocket Pond watersheds occurs to watershed nitrogen loads that pass through Lower Creek, Pease Point Brook, and the Black Brook (Section IV.2).

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 Menemsha Pond and Squibnocket 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 and potential additional development on existing developed lots.

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 (*e.g.*, state class land use codes 130 and 131 for residential properties). Properties classified by the town assessors as "undevelopable" (*e.g.*, code 132) were not assigned any development at buildout. Project staff typically reviews these initial results with local experts, the MVC staff in this case, to produce a final MEP buildout assessment.

Table IV-2. Menemsha Pond-Squibnocket Pond Embayment System Watershed Nitrogen Loads. Present nitrogen loads are based on current conditions, including septic system wastewater, residential fertilizer loads and runoff from roads. Buildout loads include septic, fertilizers, and impervious surface additions from developable properties. All values are kg N yr^{-1}.

		Menemsha Pond N Loads by Input (kg/yr):							***Present N Loads***			***Buildout N Loads***		
Name	**Watershed ID#**	**Wastewater**	**Turf Fertilizers**	**Agricultural Animals**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Menemsha Pond System Total		3,680	306	6	534	4,248	365	1,643	9,140		8,887	10,782		10,498
Lower Creek	1	336	30	-	42	-	11	53	421	60%	168	473	60%	189
Pease Point Brook	2	218	20	-	37	-	34	136	308	0%	308	444	0%	444
Nashaquitsa Pond	3	1,121	102	-	162	-	103	491	1,487	0%	1,487	1,978	0%	1,978
Menemsha Creek	4	1,352	96	-	150	-	81	186	1,679	0%	1,679	1,865	0%	1,865
Menemsha Main	5	653	59	6	143	-	136	778	996	0%	996	1,774	0%	1,774
Nashaquitsa Pond Estuary Surface Area						609			609		609	609		609
Menemsha Creek Estuary Surface Area						518			518		518	518		518
Menemsha Main Estuary Surface Area						3,122			3,122		3,122	3,122		3,122

		Squibnocket Pond N Loads by Input (kg/yr):							***Present N Loads***			***Buildout N Loads***		
Name	**Watershed ID#**	**Wastewater**	**Turf Fertilizers**	**Landfill**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Squibnocket Pond System Total		758	68	8	140	3,308	223	1,253	4,506		4,506	5,759		5,759
Black Brook	1	119	10	8	32	-	36	143	204	0%	204	347	0%	347
Squibnocket East	2	185	17	-	35	-	39	83	274	0%	274	358	0%	358
Squibnocket Main	3	455	41	-	74	20	149	1,027	740	0%	740	1,766	0%	1,766
Squibnocket East Estuary Surface Area						408			408		408	408		408
Squibnocket Main Estuary Surface Area						2,880			2,880		2,880	2,880		2,880

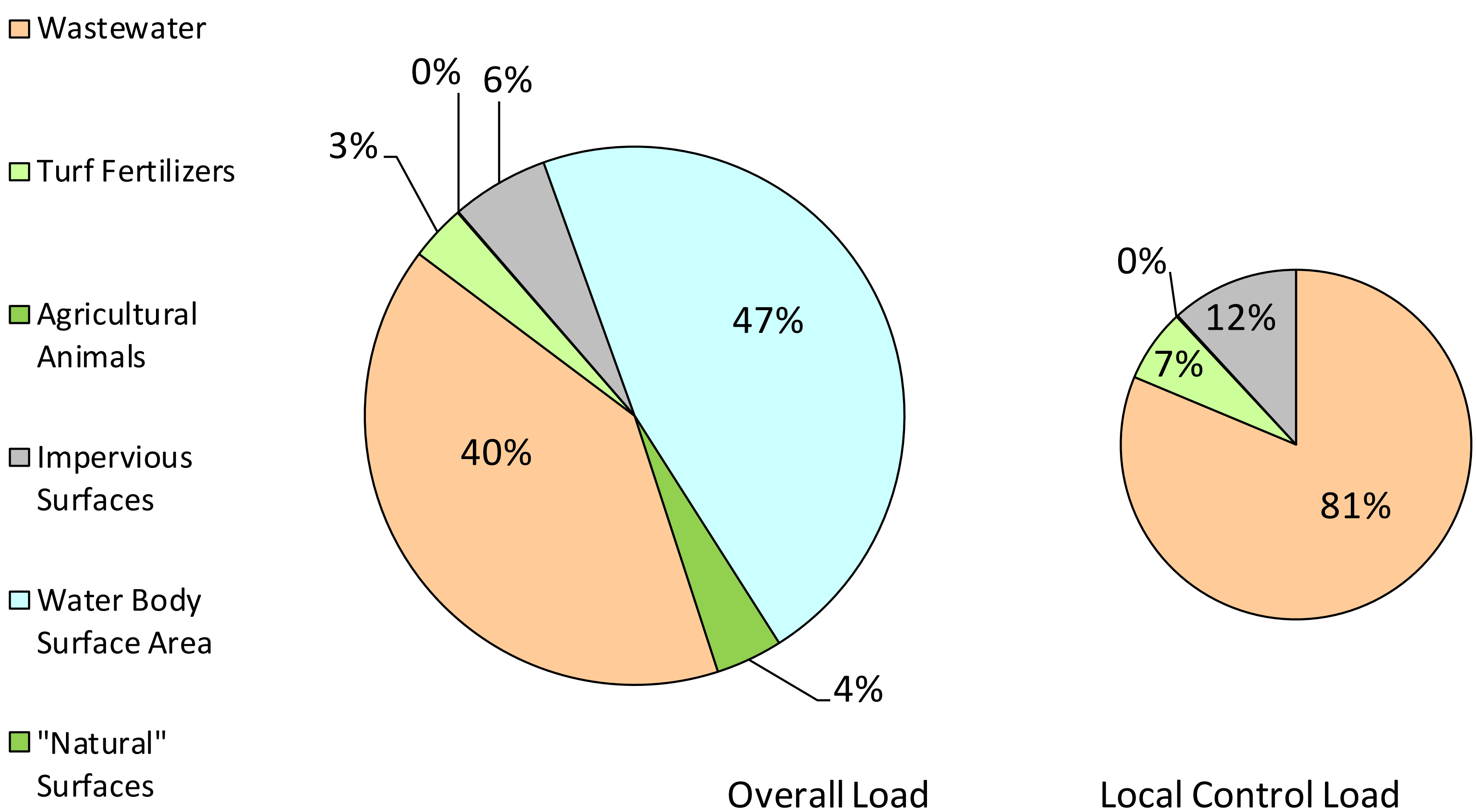

Figure IV-4a. Unattenuated nitrogen load (by percent) for land use categories within the overall Menemsha Pond watershed. “Overall Load” is the total nitrogen input within the watershed, while the “Local Control Load” represents only those nitrogen sources that could potentially be under local regulatory control.

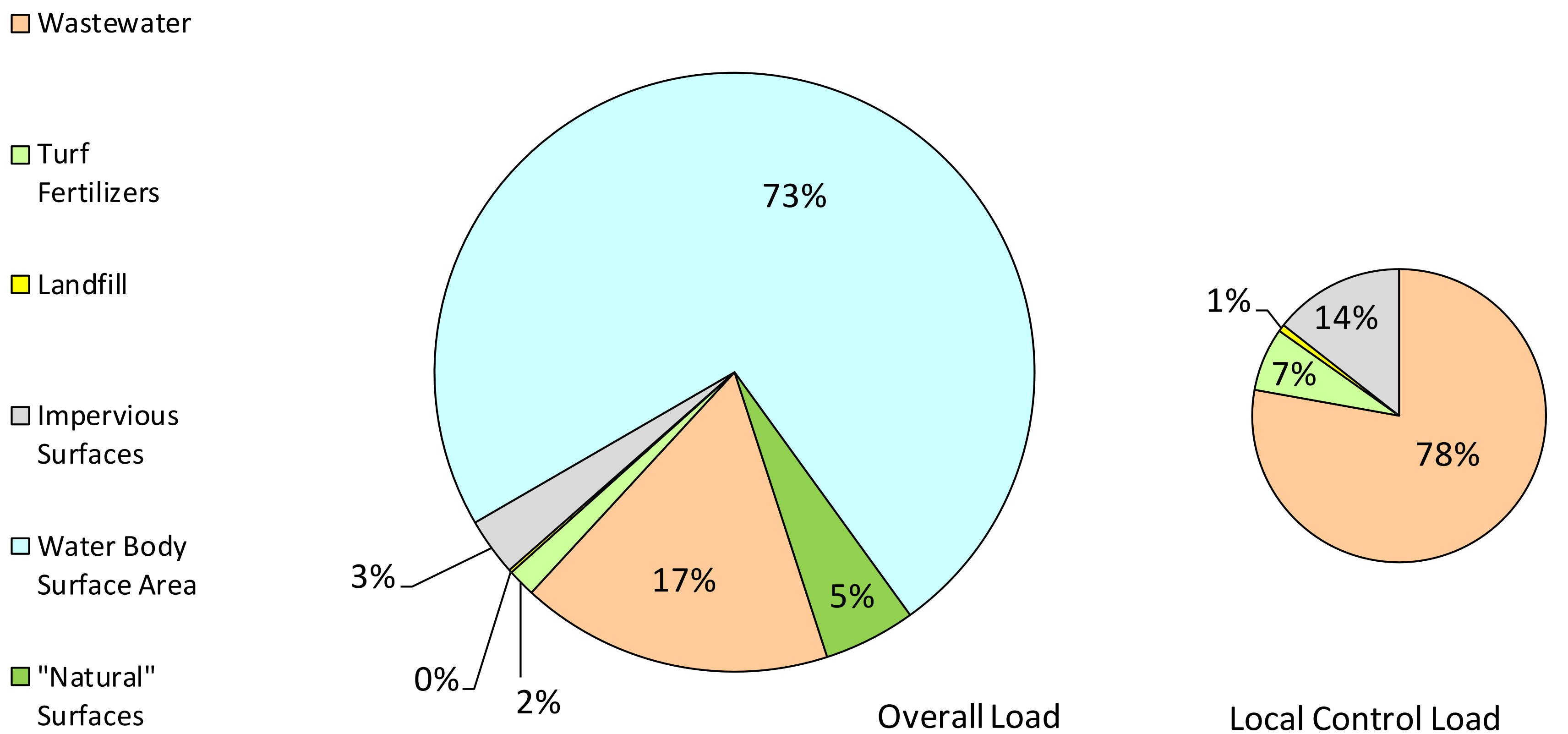

Figure IV-4b. Unattenuated nitrogen load (by percent) for land use categories within the overall Squibnocket Pond watershed. “Overall Load” is the total nitrogen input within the watershed, while the “Local Control Load” represents only those nitrogen sources that could potentially be under local regulatory control.

Based on the buildout assessment completed for this review, there are 218 and 166 potential additional residential dwellings within the Menemsha Pond and Squibnocket Pond watersheds, respectively. There is no potential additional commercial or industrial developable land. All parcels included in the buildout assessments of the Menemsha Pond and Squibnocket Pond watersheds are shown in Figure IV-5.

Nitrogen loads were developed for these buildout additions based largely on existing development factors within the Menemsha Pond and Squibnocket Pond watersheds. Additional buildout single-family residential dwellings were assigned a water use flow of 202 gpd, which is the same average water use assigned to developed residences in the watershed. Other factors used in the MEP buildout assessment are listed in Table IV-1. It should be noted that this is one example of a buildout scenario; alternative assumptions about future development could be developed to assess the water quality impacts of other buildout outcomes.

Table IV-2 presents a sum of the additional nitrogen loads by subwatershed for the MEP buildout scenario. This sum includes the wastewater, fertilizer, and impervious surface loads from additional residential dwellings added. Overall, MEP buildout additions within the Menemsha Pond and Squibnocket Pond system watersheds will increase the unattenuated loading rate by 18% and 28%, respectively.

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. The watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out, sewering analysis, enhanced flushing, pond/wetland restoration for natural attenuation, etc.) to changes in water quality and habitat health within the receiving estuary. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the sub-watersheds of the Menemsha-Squibnocket Pond Embayment System being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1).

If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such as the developed regions of the Menemsha-Squibnocket Pond Embayment System watershed). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. However, in most watersheds in southeastern Massachusetts, some portion of the watershed nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the watershed for the Menemsha-Squibnocket Pond Embayment System, a portion of the freshwater flow and transported nitrogen passes through three surface water systems (e.g. Black Brook, a small creek discharging to

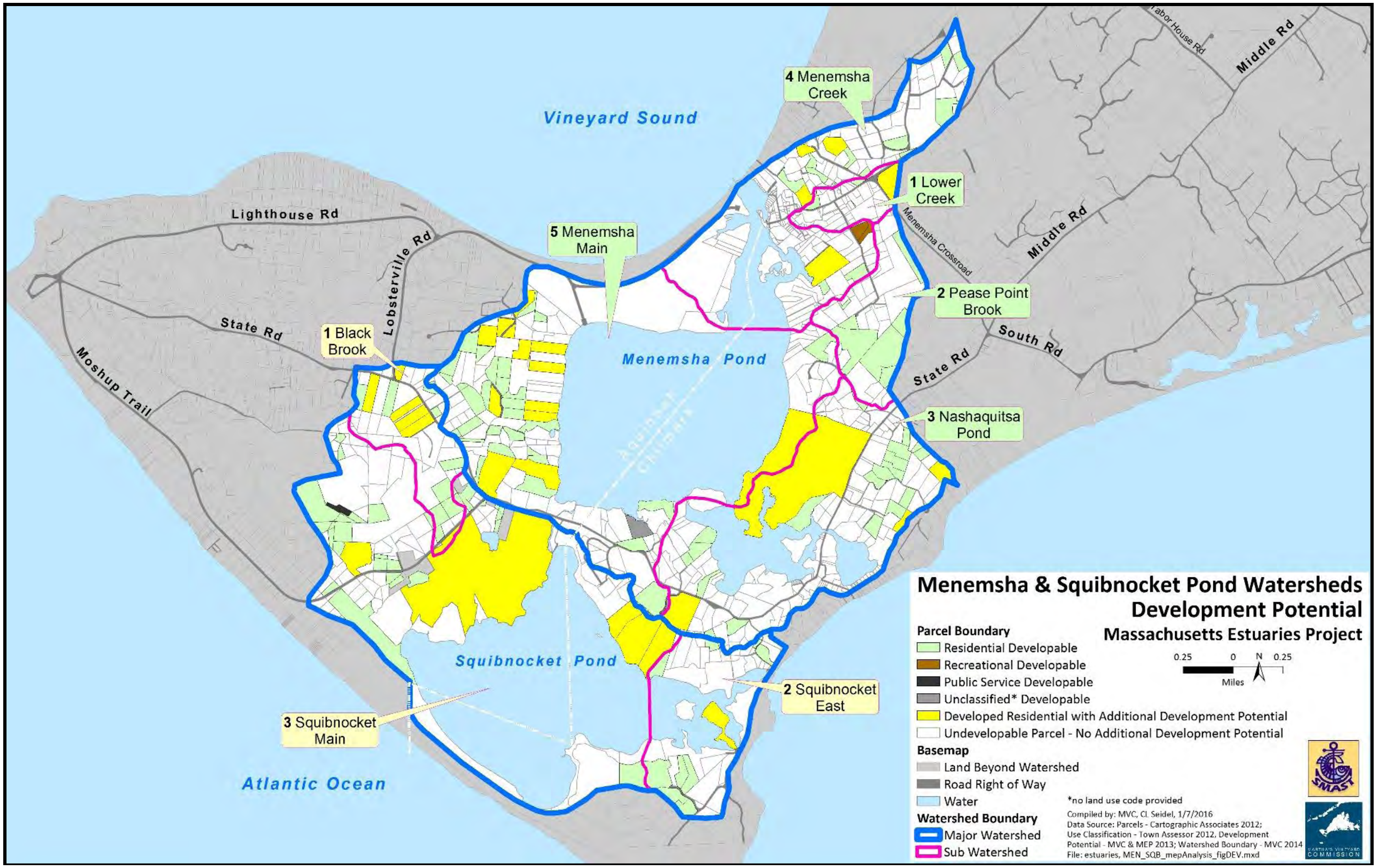

Figure IV-5. Developable Parcels in the Menemsha Pond and Squibnocket Pond watersheds. Developable parcels and developed parcels with additional development potential are highlighted. The parcels are selected based on town assessors' land use classifications and review of minimum lot sizes in town zoning regulations. Nitrogen loads in the MEP buildout scenario are based on additional development assigned to these parcels.

Pease Point and a small un-named creek discharging to the inner turning basin of Menemsha Pond close to the inlet to the overall system). All three creeks produce the opportunity for nitrogen attenuation during transport (Figure IV-5).

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

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP approach in the Menemsha-Squibnocket Pond Embayment System. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the estuary in addition to the natural attenuation measures by fresh kettle ponds in the overall watershed (as appropriate and as data was available), addressed above (Section IV.1). These additional site-specific studies were conducted in the 3 main surface water flow systems in the Menemsha-Squibnocket Pond System watershed, 1) Black Brook discharging to Squibnocket Pond, 2) Pease Point Creek and 3) an un-named creek discharging to Menemsha Creek prior to entry to Menemsha Pond. Together these 3 small streams serve as "drains" of watershed groundwater accounting for 13% and 16% of the total freshwater discharge from the watersheds to Menemsha Pond and Squibnocket Pond, respectively.

Quantification of watershed based nitrogen attenuation is contingent upon being able to compare nitrogen load to the embayment system directly measured in freshwater stream flow (or in tidal marshes, net tidal outflow) to nitrogen load as derived from the detailed land use analysis (Section IV.1). Measurement of the flow and nutrient load associated with the freshwater streams discharging to an embayment provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up-gradient from the gauging sites. In the present effort, flow and nitrogen load were measured at each of the 3 gauges in each freshwater stream site for between 12 and 18 months of record depending on the stream gauging location (Figure IV-6). For each time-series period, velocity profiles were completed on each stream every month to two months.

Figure IV-6. Location of stream gauges (red symbols) in the Menemsha and Squibnocket Pond Embayment System watershed.

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

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

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

where by:

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

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

Periodic measurement of flows over the entire stream gauge deployment period allowed for the development of a stage-discharge relationship (rating curve) that could be used to obtain flow volumes from the detailed record of stage measured by the continuously recording stream gauges. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given river. These hourly stages values were then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. In the case of tidal influence on stream stage, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of strictly freshwater flow. The lowest tide stage value for a given day was extracted from all the other stage values on a specific day and that lowest stage was then entered into the stage – discharge relation in order to compute daily flow. The lowest stage value in a tidally influenced stream was used as it is most representative of freshwater flow. A complete annual record of stream flow (365 days) was generated for each of the 3 surface water discharges flowing into the Menemsha-Squibnocket Pond Embayment System.

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

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Black Brook Discharge to Squibnocket Pond

Unlike most surface water features in the MEP study region that typically emanate from a specific pond, Black Brook, which discharges into the western portion of Squibnocket Pond, does not have an up-gradient freshwater pond from which that brook discharges. Rather, this small stream appears to be groundwater fed, The stream originates in a boggy low land (based upon topographic map) and the wooded area up-gradient of the gauge located at the Moshup Trail Road crossing of Black Brook provides for a direct measurement of the nitrogen attenuation, likely associated with the wetland areas. The combined rate of nitrogen attenuation by the biological processes occurring as the water in Black Brook flows to the estuary was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the gauge site and the measured annual discharge of nitrogen to Squibnocket Pond at the gauge site, Figure IV-6.

The freshwater flow carried by Black Brook to the brackish waters of Squibnocket Pond was determined using a continuously recording vented calibrated water level gauge. As this surface water system was potentially tidally influenced, the creek discharge was checked to confirm the extent of tidal influence and whether freshwater flow could be measured at low tide in the estuary. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average measured sample salinity was found to be $\leq$0.1 ppt, indicating only freshwater flow. As such, a salinity adjustment was not necessary in order to determine daily flows using the MEP developed stage-discharge relation. The Black Brook gauge location was deemed acceptable for making flow measurements and obtaining an estimate of annual freshwater flow and nitrogen load. Calibration of the gauge was checked monthly. The gauge was installed on April 25, 2006 and was set to operate continuously for 16 months such that at least one summer season would be captured in the flow record. Stage data collection continued until December 4, 2007 for a total deployment of 19 months.

Stream flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the gauge site based upon these flow measurements and the measured water levels at the gauge site. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge from Black Brook to the western portion of Squibnocket Pond and incorporates the biological processes occurring in the stream channel, wetlands and wooded areas contributing to nitrogen attenuation (Figure IV-7 and Table IV-3 and IV-4). In addition, a water balance was constructed based upon the Martha's Vineyard Commission (MVC)/MEP defined watershed delineations to determine long-term average freshwater discharge expected at the Black Brook gauge site based on area and average recharge.

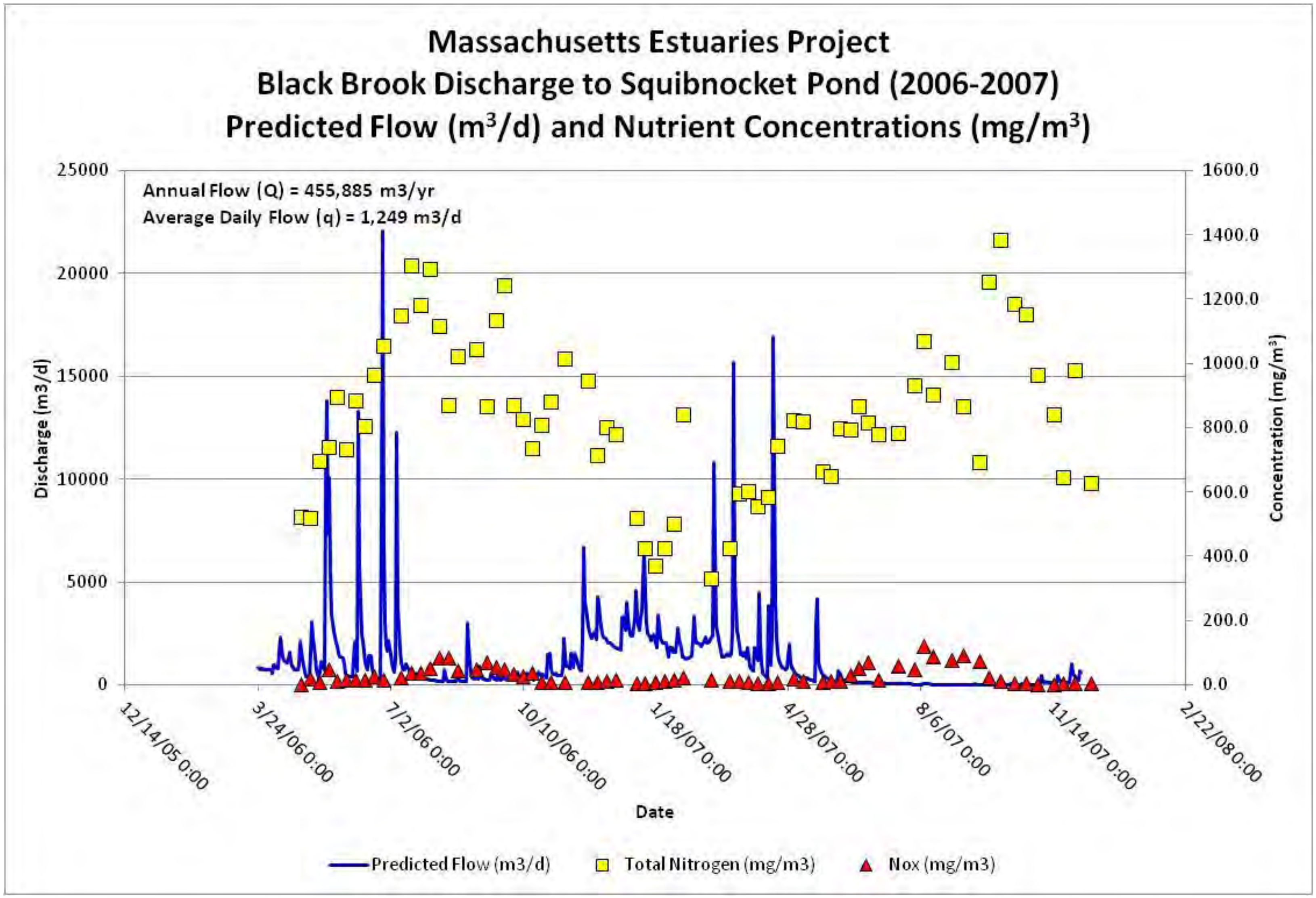

Figure IV-7. Black Brook volumetric discharge (solid blue line) and concentrations of total nitrogen (yellow symbols) and Nitrate+Nitrite - NOx (red symbols) for determination of annual discharge and nitrogen load from the sub-watershed of Black Brook to the western portion of Squibnocket Pond (Table IV-3).

The annual freshwater flow record for Black Brook as measured by the MEP was compared to the long-term average flows determined by the MVC/MEP delineation effort (Table III-1). The measured freshwater discharge from Black Brook at the Moshup Trail gauge location was 4% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for the hydrologic year beginning September 2006 and ending in August 2007 (low flow to low flow) was 1,363 m^3/day compared to the long term average flows determined by the watershed modeling effort (1,416 m^3/day). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Black Brook discharging from the sub-watershed indicates that the Brook is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Black Brook outflow were low to moderate, 0.638 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 0.80 kg/day and a measured total annual TN load of 291 kg/yr. In Black Brook, nitrate made up an insignificant fraction of the total nitrogen pool (2%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the wetland areas and stream bed up-gradient of the gauge was almost completely taken up by plants and transformed to organic forms (85% of total nitrogen pool). Given the extremely low levels of remaining nitrate in the stream discharge, the possibility for additional uptake by freshwater systems is extremely limited in the Black Brook sub-watershed.

From the measured nitrogen load discharged by Black Brook to Squibnocket Pond and the nitrogen load determined from the watershed based land use analysis, it appears that there is no significant nitrogen attenuation of watershed derived nitrogen during transport via Black Brook to Squibnocket Pond. Based upon the nearly similar total nitrogen load (291 kg yr^{-1}) discharged from Black Brook at Moshup Trail compared to that added by the various land-uses to the associated watershed (204 kg yr^{-1}), the integrated attenuation in passage through the stream and up-gradient freshwater wetlands is considered to be zero. Nitrogen input to watershed reaches the estuary unattenuated. This level of attenuation compared to other streams evaluated under the MEP (for example Kirby Brook and Snell Creek in the Westport River estuary {0.2% and 6% attenuation respectively}) is expected given the nature of the up-gradient wooded areas which lack significant up-gradient ponds/lakes capable of attenuating nitrogen. However it is also possible that given the uncertainties in the available landfill data, that there is a higher input from that source than indicated. The directly measured nitrogen load from Black Brook was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

Table IV-3. Comparison of water flow and nitrogen load discharged by Black Brook, Pease Point Brook and an unnamed brook associated with Menemsha Creek within the Menemsha Pond-Squibnocket Pond Embayment System watershed. The "Stream" data are from the MEP stream gauging effort. Watershed data are based upon the MEP watershed land-use modeling effort (Section IV.1) and the MVC-MEP watershed delineation (Section III).

Stream Discharge Parameter	Black Brook Discharge[(a)] Squibnocket Pond	Pease Point Brook Discharge[(a)] Menemsha Channel	Un-named Brook Discharge[(a)] Menemsha Basin	Data Source
Total Days of Record	365[(b)]	365[(b)]	365[(b)]	(1)
Flow Characteristics				
Stream Average Discharge (m3/day)	1,363	1,308	534	(1)
Contributing Area Average Discharge (m3/day)	1,416	1382	555	(2)
Discharge Stream 2006-07 vs. Long-term Discharge	-3.89%	-5.66%	-3.93%	
Nitrogen Characteristics				
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.013	0.078	0.277	(1)
Stream Average Total N Concentration (mg N/L)	0.638	0.685	0.775	(1)
Nitrate + Nitrite as Percent of Total N (%)	2%	11%	36%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	0.80	0.896	0.41	(1)
TN Average Contributing UN-attenuated Load (kg/day)	0.56	0.84	1.15	(3)
Attenuation of Nitrogen in Pond/Stream (%)	0%	0%	64%	(4)

(a) Flow and N load to streams discharging to Menemsha and Squibnocket Ponds includes apportionments of Pond contributing areas as appropriate.
(b) Average September 1, 2006 to August 31, 2007.

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

Table IV-4. Summary of annual volumetric discharge and nitrogen load from Black Brook to Squibnocket Pond, Pease Point Creek to Lower Menemsha Pond and an un-named creek to Menemsha Creek. Summary of flows and loads are based on data presented in Figures IV-6, IV-7, IV-8 and Table IV-3.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Squibnocket Pond Black Brook MEP	**September 1, 2006 to August 31, 2007**	**455,885**	**6**	**291**
Squibnocket Pond Black Brook (MVC)	Based on Watershed Area and Recharge	**516,840**	--	--
Menemsha Pond Pease Point Creek MEP	**September 1, 2006 to August 31, 2007**	**477,420**	**37**	**327**
Menemsha Pond Pease Point Creek (MVC)	Based on Watershed Area and Recharge	**504,430**	--	--
Menemsha Pond (inner basin) Un-Named Creek MEP	**September 1, 2006 to August 31, 2007**	**194,910**	**54**	**151**
Menemsha Pond (inner basin) Un-Named Creek (MVC)	Based on Watershed Area and Recharge	**202,575**	--	--

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Pease Point Creek discharge to Menemsha Pond

Unlike most surface water features in the MEP study region that typically emanate from a specific pond, the Pease Point creek discharge to Menemsha Pond does not have an up-gradient pond from which it discharges. Rather, this small creek appears to be groundwater fed and emanates from a mostly wooded and somewhat boggy area (based on topography map) up-gradient of Pease Point Road. The creek outflow from the boggy low land as the source water to the creek and the wooded area up-gradient of the gauge may potentially attenuate nitrogen. The gauge is located at the Pease Point Road crossing of the creek and provides for a direct measurement of volumetric flow, nitrogen load and attenuation. The integrated rate of nitrogen attenuation by the biological processes occurring as the water in the creek flows to the estuary was determined by comparing the present predicted nitrogen loading from its sub-watershed contributing to the bog/wetland and wooded areas above the gauge site and the measured annual discharge of nitrogen to the Menemsha Pond portion of the estuary relative to the gauge, Figure IV-6.

The freshwater flow carried by the Pease Point Creek to the estuarine waters of Menemsha Pond was determined using a continuously recording vented calibrated water level gauge. As this surface water system was potentially tidally influenced, the creek discharge was checked to confirm the extent of tidal influence and whether freshwater flow could be measured at low tide in the estuary. To confirm that freshwater was being measured, salinity measurements were conducted on weekly water quality samples collected from the gauge site. Average measured sample salinity was found to be $\leq$0.1 ppt, indicating that the stream is transporting only freshwater to the gauge site. As such, a salinity adjustment was not necessary in order to determine daily flows using the MEP developed stage-discharge relation. The Pease Point Creek gauge location was deemed acceptable for making flow measurements and obtaining an estimate of annual freshwater flow and nitrogen load. Calibration of the gauge was checked monthly. The gauge was installed on April 25, 2006 and was set to operate continuously for 16 months such that at least one summer season would be captured in the flow record. Stage data collection continued until December 4, 2007 for a total deployment of 19 months.

Stream flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the gauge site based upon these flow measurements and the measured water levels at the gauge site. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge through the gauge site to the lower portion of Menemsha Pond and integrates the biological processes occurring in the stream channel, wetlands and wooded areas causing nitrogen attenuation (Figure IV-8 and Table IV-3 and IV-4). In addition, a water balance was constructed based upon the Martha's Vineyard Commission (MVC)/MEP defined watershed delineations to determine long-term average freshwater discharge expected at the Pease Point Creek gauge site based on contributing area and average recharge.

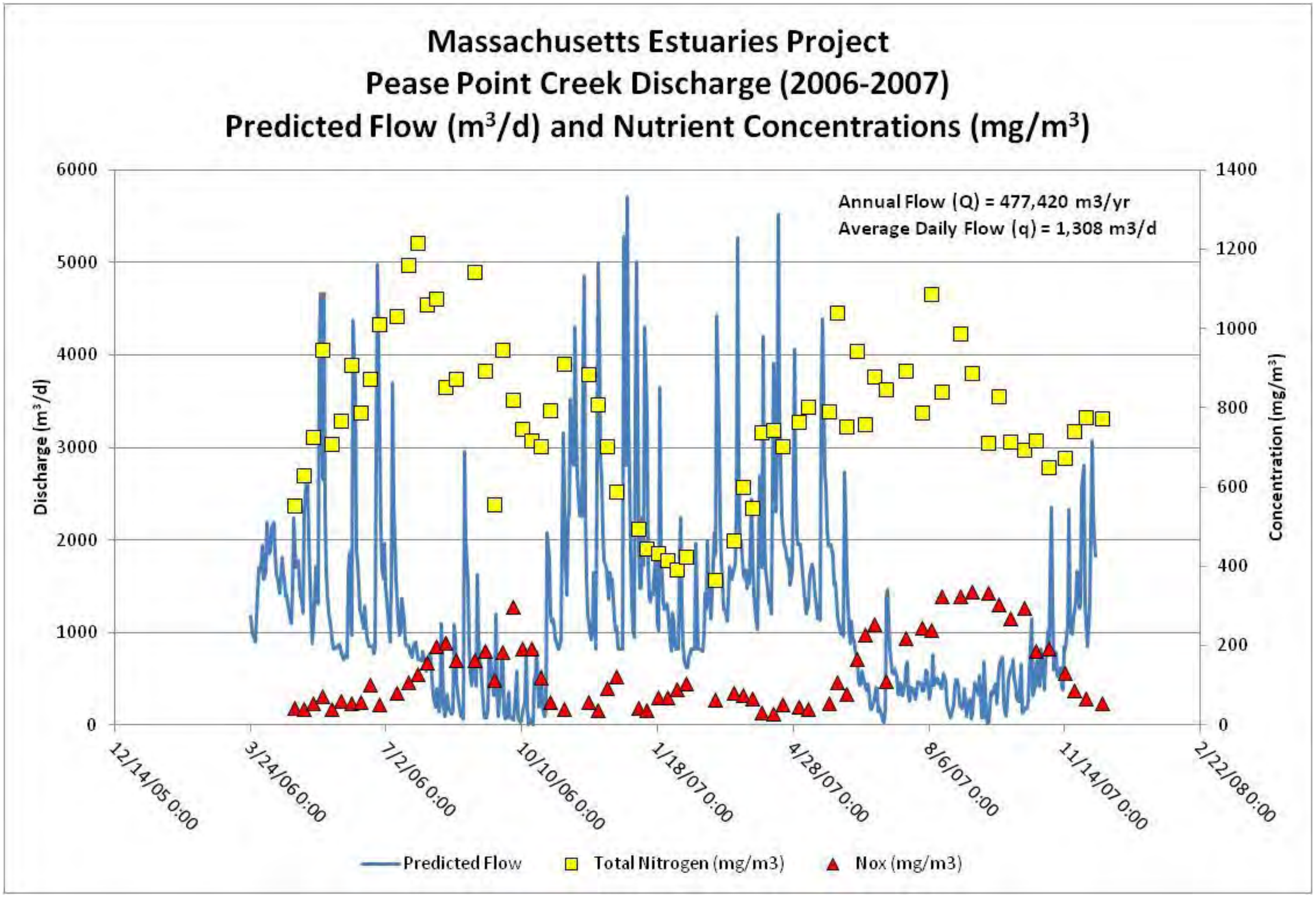

Figure IV-8. Pease Point Creek volumetric discharge (solid blue line) and concentrations of total nitrogen (yellow symbols) and Nitrate+Nitrite - NOx (red symbols) for determination of annual discharge and nitrogen load from the sub-watershed of Black Brook to the lower portion of the Menemsha Pond basin (Table IV-3).

The annual freshwater flow record for Pease Point Creek as measured by the MEP was compared to the long-term average flows determined by the MVC/MEP delineation effort (Table III-1). The measured freshwater discharge from the creek at the Pease Point Road gauge location was <6% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for the hydrologic year beginning September 2006 and ending in August 2007 (low flow to low flow) was 1,308 m^3/day compared to the long term average flows determined by the watershed modeling effort (1,382 m^3/day). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Pease Point Creek discharging from the sub-watershed indicates that the creek is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Pease Point Creek outflow were low to moderate, 0.685 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 0.90 kg/day and a measured total annual TN load of 327 kg/yr. In Black Brook, nitrate made up a very small fraction of the total nitrogen pool (11%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the wetland areas and stream bed up-gradient of the gauge was almost completely taken up by plants and converted to organic nitrogen forms (88% of total nitrogen pool). The characteristics of this creek are very similar to Black Brook that showed a similar flow from a similar up-gradient sub-watershed and resulting in similar nutrient concentrations and loads. Given the extremely low levels of remaining nitrate in the stream discharge, the possibility for additional uptake by freshwater systems is extremely limited in the Pease Point Creek sub-watershed.

From the measured nitrogen load discharged by Pease Point Creek to lower Menemsha Pond and the nitrogen load determined from the watershed based land use analysis, it appears that there is no significant nitrogen attenuation of watershed derived nitrogen during transport to the Pease Point Creek gauge and into Menemsha Pond. Based upon the similar total nitrogen load (327 kg yr^{-1}) discharged from Pease Point Creek at Pease Point Road compared to that added by the various land-uses to the associated watershed (308 kg yr^{-1}), the integrated attenuation in passage through the stream and up-gradient freshwater wetlands prior to discharge to the estuary is considered to be zero. Nitrogen input to watershed reaches the estuary unattenuated. This level of attenuation compared to other streams evaluated under the MEP (for example Kirby Brook and Snell Creek in the Westport River estuary {0.2% and 6% attenuation respectively}) is expected given the nature of the up-gradient wooded areas which lack significant up-gradient ponds/lakes capable of attenuating nitrogen and is also very similar to Black Brook discharging to Squibnocket Pond. The directly measured nitrogen load from Pease Point Creek was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

IV.2.4 Surface water Discharge and Attenuation of Watershed Nitrogen: Un-named Creek to Inner Turning Basin of Menemsha Pond (Lower Creek)

Unlike most surface water features in the MEP study region that typically emanate from a specific pond, the un-named creek (referred to as Lower Creek in the MEP nitrogen loading model described in Section IV.1) which discharges into the inner turning basin of Menemsha Pond does not have an up-gradient pond from which it discharges. Rather, this small creek appears to be groundwater fed and emanates from a wooded area up-gradient of North Road. The stream outflow from the marshy / wooded area up-gradient of the gauge located at the North Road crossing of the creek may serve to contribute to the attenuation of nitrogen and also provides for a direct measurement of the nitrogen attenuation. The integrated rate of nitrogen attenuation by the biological processes occurring as the water in the creek flows to the estuary was determined by comparing the present nitrogen loading estimated from the land-use model to the gauge site to that measured directly at the gauge site., Figure IV-6.

The freshwater flow carried by the creek to the estuarine waters of Menemsha Pond was determined using a continuously recording vented calibrated water level gauge. As this surface water system was potentially tidally influenced, the creek discharge was checked to confirm the extent of tidal influence and whether freshwater flow could be measured at low tide in the estuary. To confirm that freshwater was being measured, salinity measurements were conducted on weekly water quality samples collected from the gauge site. Average measured sample salinity was found to be $\leq$0.1 ppt, indicating that the creek was only transporting freshwater. As such, a salinity adjustment was not necessary in order to determine daily flows using the MEP developed stage-discharge relation. The gauge location on this un-named creek was deemed acceptable for making flow measurements and obtaining an estimate of annual freshwater flow. Calibration of the gauge was checked monthly. The gauge was installed on May 23, 2006 and was set to operate continuously for 16 months such that at least one summer season would be captured in the flow record. Stage data collection continued until September 22, 2007 for a total deployment of 16 months.

Stream flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the gauge site based upon these flow measurements and the measured water levels at the gauge site. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge to the inner turning basin situated in the lower portion of Menemsha Pond close to the inlet to the overall system and includes biological processes contributing to nitrogen attenuation (Figure IV-9 and Table IV-3 and IV-4). In addition, a water balance was constructed based upon the Martha's Vineyard Commission (MVC)/MEP defined watershed delineations to determine long-term average freshwater discharge expected at the creek gauge site based on area and average recharge.

The annual freshwater flow record for the creek discharging to the inner turning basin of Menemsha Pond as measured by the MEP was compared to the long-term average flows determined by the MVC/MEP watershed delineation effort (Table III-1). The measured freshwater discharge from the creek at the North Road gauge location was only 4% below the long-term average modeled volumetric discharge. The average daily flow based on the MEP measured flow data for the hydrologic year beginning September 2006 and ending in August 2007 (low flow to low flow) was 534 m^3/day compared to the long term average flows determined by the watershed modeling effort (555 m^3/day). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the un-named creek discharging from the sub-watershed indicates that the creek is capturing the up-gradient recharge (and loads) accurately.

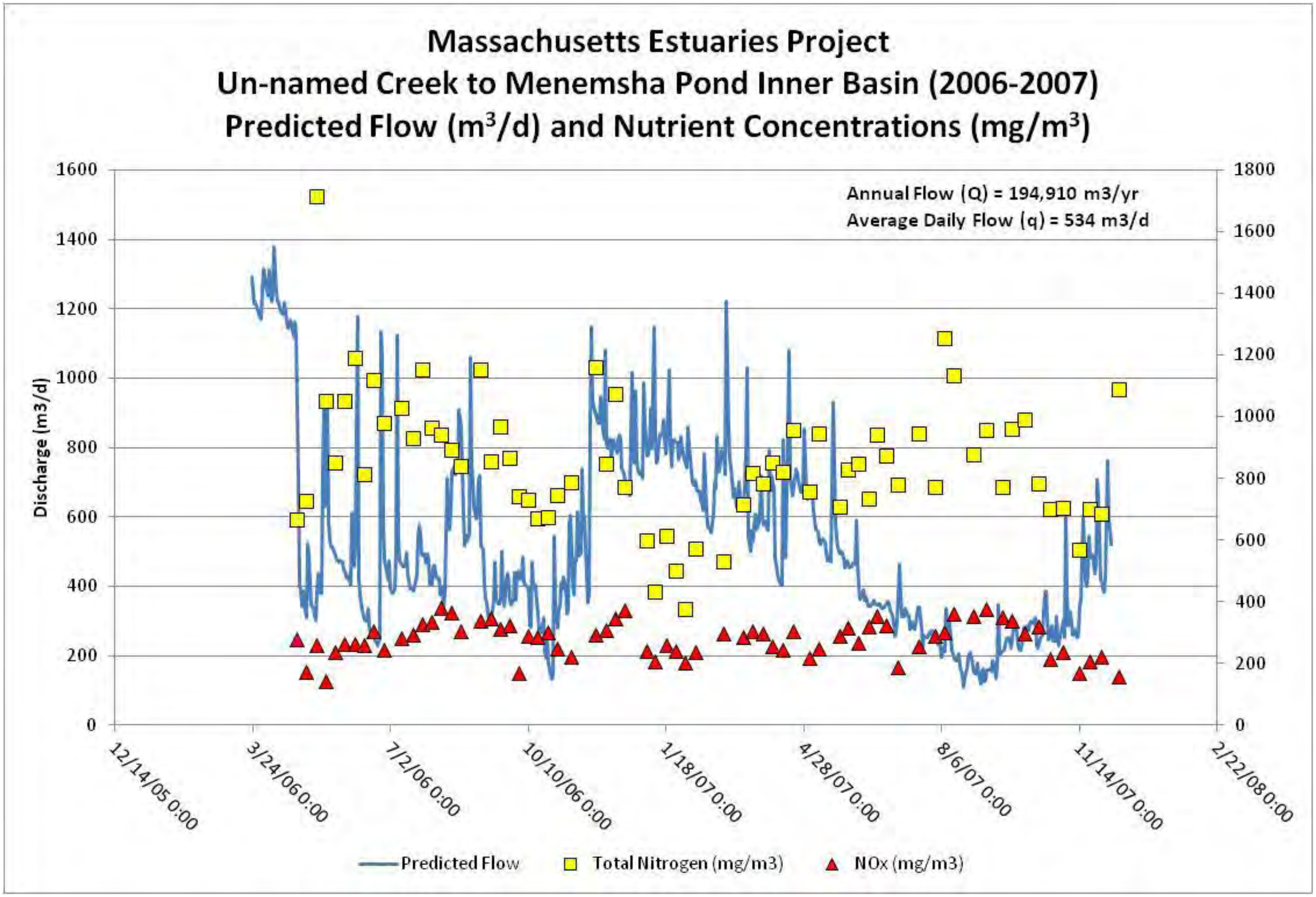

Figure IV-9. Un-named Creek to Menemsha Creek, volumetric discharge (solid blue line) and concentrations of total nitrogen (yellow symbols) and Nitrate+Nitrite - NOx (red symbols) for determination of annual discharge and nitrogen load from the sub-watershed of the creek upgradient of the gauge (Table IV-3).

Total nitrogen concentrations within the creek outflow were moderate, 0.775 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 0.41 kg/day and a measured total annual TN load of 151 kg/yr. In the creek discharge, nitrate made well less than half of the total nitrogen pool (36%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the riparian zone areas and stream bed up-gradient of the gauge was partially taken up by plants and converted to organic nitrogen forms. Interestingly, uptake of nitrate+nitrite was less than that observed in Black Brook and the Pease Point Creek. Nevertheless, given the relatively low levels of remaining nitrate in the creek discharge, the possibility for additional uptake by freshwater systems might be limited in the sub-watershed to this small creek.

From the measured nitrogen load discharged by the creek flowing to Menemsha Creek and the nitrogen load determined from the watershed based land use analysis, it appears that there is significant nitrogen attenuation of upper watershed derived nitrogen during transport to the gauge site and Menemsha Pond. Based upon the much lower total nitrogen load (151 kg yr^{-1}) discharged from the creek at North Road compared to that added by the various land-uses to the associated watershed (421 kg yr^{-1}), the integrated attenuation in passage through the stream and up-gradient freshwater riparian zones and wooded areas prior to discharge to the estuary is 64% (i.e. 64% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is common in areas with vegetated riparian zone, stream channels and flow through wetland areas. The directly measured nitrogen load from the creek was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

IV.2.5 Surface water Exchange Between Squibnocket Pond and Menemsha Pond - Herring Creek Tidal Flux Results

Two tidal flux investigations (August 2,15, 2010) to obtain measurements of tidal inflow and outflow through the existing culvert connecting Menemsha Pond to Squibnocket Pond and passing under State Street (Figure IV-10, IV-11) were undertaken by the MEP Technical Team. Each tidal flux provided: (1) an estimate of salt and nitrogen exchange between the two ponds and (2) direct measurements of volume exchanged over a complete tidal cycle to inform the hydrodynamic modeling effort conducted by Applied Coastal Research and Engineering.

Each tidal flux event took place on a neap tide (quarter moon) over a single complete tidal cycle beginning approximately 1 hour before low tide and ending approximately 1 hour after the following low tide. Before each tidal flux, it was determined that there was no precipitation for at least one complete tidal cycle prior to the first time point to ensure that water and nutrient flux data would not be biased by rain-related flows. Water samples were collected at the culvert at regular intervals (<1 hr) over the course of the tidal cycle. Samples were analyzed for temperature, salinity and total nitrogen. Flood and ebb current velocity measurements and channel cross-section water depths were made concurrently with water sample collections at the culvert to determine volumetric flow through the culvert throughout both flood and ebb tides. These flow data were then interpolated to yield a detailed record of total volumetric flow into and out of Squibnocket Pond. Total flow into Squibnocket Pond was calculated between slack low tide and slack high tide. Total flow out was calculated from slack high tide to the point at which the tidal height during ebb reached the same level as that recorded at the previous slack low tide, as measured by the tide gauge (Figure IV-11) deployed up-gradient of the State Street culvert on an ebbing tide.

Figure IV-10 Menemsha Pond - Squibnocket Pond Embayment System. Red oval indicates the location of the herring run connecting the two basins. August 2010 tidal fluxes conducted at the culvert passing under the roadway.

Figure IV-11. Location of tide gauge deployed in Herring Creek to measure stage during the 08/02/10 (1 day off the quarter moon, neap tide) and 08/15/10 (1 day off the quarter moon, neap tide) tidal sampling events. During the 2010 tidal flux studies a stage recorder was positioned up-gradient of the State Road culvert.

Flow measurements and sample concentrations during flood and ebb tides was used to calculate the mass flux of water, salt and total nitrogen (TN) into and out of Squibnocket Pond on each of the 2 sampling dates. Data from each collected water sample was paired with the corresponding flow rate to calculate a mass flux of each constituent at each sampling time over a complete tidal cycle. These results were interpolated to yield a total mass flux for the entire tidal cycle (i.e. the total out minus the total in = net flux). From these tidal exchange data, the magnitude and direction of the net flux of water, salt and TN were calculated. As salinity in Squibnocket Pond is conservative, the MEP Technical Team balanced the exchange of salt on both the ebb and flood tides in order to determine the net exchange of water and total nitrogen between Squibnocket Pond and Menemsha Pond.

Mass Flux of Salt. As a conservative tracer and a good measure of dilution effects when higher salinity water mixes with fresher water as is found in Squibnocket Pond. Salinity was monitored during each of the two tidal fluxes completed in August 2010. Since salinity in Squibnocket Pond is conservative (unaffected by biological processes), it was used to refine the measures of volumetric exchange such that salt is conserved, no more salt enters than leaves the system. Once the flow volume was determined over both the flood and ebb portions of the tidal cycle, the flow was salinity adjusted such that the mass of salt (kg) into Squibnocket Pond equaled the mass of salt leaving (Tables IV-5, IV-6). During the August 2 flux, 62,124 kg entered the pond and 62,124 kg exited on the ebb tide. During the August 15 flux the mass of salt in and out was a little higher (78,903 kg) reflecting the slighter large change in tidal stage (low tide to high tide) compared to the August 2 conditions.

Tidal Exchange Volumes. Total volumetric exchange over the 2 tidal cycles measured on flooding tides ranged from 1,021 cubic meters on August 2 to 2,628 cubic meters on August 15 (Table IV-5) compared to ebbing tides, which ranged from 3,256 cubic meters on August 02 to 4,824 cubic meters on August 15 (Table IV-6). Water flux during tidal ebb was of a longer duration than during tidal flooding. Each of the tidal cycles measured showed a greater volume of water exiting Squibnocket Pond on the ebbing tide than entering on the preceding flooding tide. This volumetric difference, results from the entry of freshwater from stream flow and groundwater seepage into the Pond. The observations and volumetric effect of freshwater on tidal inflow versus outflow has been documented for a variety of salt marsh and embayment systems on Cape Cod (Millham and Howes 1994, Smith 1999, Valiela et al. 1978). The result of the interaction of freshwater inflows and tidal hydrodynamics is that the volume of water on the ebb tide is greater than on the flood tide (Table IV-5,6). The net outflow volumes from the two samplings were nearly identical at 2,235 cubic meters and 2,196 cubic meters on August 2nd and 15th, respectively. The net volumetric outflow (average daily) is approximately half of the annual average daily groundwater flow into Squibnocket Pond from the watershed. However, the tidal studies were conducted during the period of lowest stream and groundwater inflows of the year. This can be seen in the low average daily flow observed in Black Brook to Squibnocket Pond in August (356 m^3/d) compared to the annual average daily inflow of 1,363 $m^3\ d^{-1}$. This is also consistent with the lower direct input of freshwater from precipitation, which is also at a low in August. When adjusted for the seasonality of freshwater inputs to Squibnocket Pond, it appears that the net outflow of water as measured in the tidal studies is properly accounting for the freshwater entering the pond during the measured tidal cycles.

Total Nitrogen. One approach to dealing with the transformations of nitrogen within an aquatic system like Squibnocket Pond is to focus on the total nitrogen pool. Total Nitrogen (TN) is the sum of all organic and inorganic forms of N. Based upon this analysis there was a net export of TN on both sampling dates. The net nitrogen transfer to Menemsha Pond reflects nitrogen entering Squibnocket Pond waters prior to their outflow to Menemsha Pond. This results in a net mass transfer of nitrogen of ~2.6 kg N /tidal cycle (3.13 kg/tidal cycle and 2.51 kg/tidal cycle on August 2nd and 15th, respectively, Table 5,6). This represents an average daily export of total nitrogen in August from Squibnocket Pond to Menemsha Pond of approximately 5.64 kg/day. This is 46% of the annual average daily nitrogen input to Squibnocket Pond from its watershed and atmospheric deposition (12.34 kg/day). Given that the measurements were during neap tides and a low freshwater inflow period, the net outflow of nitrogen is consistent with the input of nitrogen in August. It also appears that freshwater flows are an important part of the flushing out of nitrogen from Squibnocket Pond and help drive transfers to Menemsha Pond.

Table IV-5. Summary of Tidal Flux from the 08/02/10 sampling event. Volumetric discharge and total nitrogen load between Menemsha Pond and Squibnocket Pond. A total of two (2) tidal flux events were completed in the summer 2010 (August). Exchange was determined on a neap tide, 1 day off the quarter moon. “Flux In” and “Flux Out” indicate tidal flow into and out of Squibnocket Pond, respectively.

M.T.G.3	Water	Salt	TN
	m^3/tidal cycle	Kg/tidal cycle	(g)/tidal cycle
Flux In	1,021	62,124	455
Flux Out	3,256	62,124	3,585
Net Flux	**-2,235**	**0**	**-3,130**
Net Flux (kg)			**-3.13**
Direction	OUT	BALANCED	OUT

Table IV-6. Summary of Tidal Flux from the 08/15/10 sampling event. Volumetric discharge and total nitrogen load between Menemsha Pond and Squibnocket Pond. A total of two (2) tidal flux events were completed in the summer 2010 (August). Exchange was determined on a neap tide, 1 day off the quarter moon. “Flux In” and “Flux Out” indicate tidal flow into and out of Squibnocket Pond, respectively

M.T.G.3	Water	Salt	TN
	m^3/tidal cycle	Kg/tidal cycle	(g)/tidal cycle
Flux In	2,628	78,903	1,075
Flux Out	4,824	78,903	3,585
Net Flux	**-2,196**	**0**	**-2,510**
Net Flux (kg)			**-2.51**
Direction	OUT	BALANCED	OUT

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the benthic nutrient flux survey was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters throughout the Menemsha Pond and Squibnocket Pond Embayment System. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems.

In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh, brackish 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 Menemsha-Squibnocket Pond Embayment System predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like the Atlantic Ocean or Vineyard 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 sediments. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with associated nitrogen “load” become incorporated into the surficial sediments of the system.

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

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial communities. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, such as found within nearby Sengekontacket Pond. In contrast, regions of high deposition like Hyannis Inner Harbor on Cape Cod, which is essentially a dredged boat basin, typically support anoxic sediments with elevated rates of nitrogen release during summer months. The consequence of this deposition is that these basin sediments are unconsolidated, organic rich and sulfidic nature (MEP field observations).

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

IV.3.2 Method for determining sediment-watercolumn nitrogen exchange

For the Menemsha-Squibnocket 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. Twenty-four sediment samples were collected from a total of 23 sites throughout the Menemsha Pond portion of the embayment system and 16 cores at 15 sites within Squibnocket Pond. The Menemsha Pond sediment sites included 3 sites within Nashaquitsa Pond and 2 sites in Stonewall Pond, (Figure IV-9). All the sediment cores for this system were collected in July-August 2007. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to the shoreside lab operated by the Wampanoag Tribe of Aquinnah. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from core sites to replace the headspace water of each core prior to incubation. The number of core samples from each estuarine component (Figure IV-12) are as follows:

Menemsha-Squibnocket Pond Benthic Nutrient Regeneration Cores

Menemsha Pond - Estuarine

- MEN-1 1 core (Menemsha Creek/Channel)
- MEN-2 1 core (Menemsha Creek/Channel)
- MEN-3 1 core (Menemsha Creek/Channel)
- MEN-4 1 core (Menemsha Creek/Channel)
- MEN-5 1 core (Menemsha Creek/Channel)
- MEN-6 1 core (Menemsha Pond Main Basin)
- MEN-7 1 core (Menemsha Pond Main Basin)
- MEN-8 1 core (Menemsha Pond Main Basin)
- MEN-9 1 core (Menemsha Pond Main Basin)
- MEN-10 1 core (Menemsha Pond Main Basin)
- MEN-11 1 core (Menemsha Pond Main Basin)
- MEN-12 1 core (Stonewall Pond)
- MEN-13 1 core (Stonewall Pond
- MEN-14 1 core (Nashaquitsa Pond)
- MEN-15 1 core (Nashaquitsa Pond)
- MEN-16 1 core (Nashaquitsa Pond)
- MEN-17 1 core (Menemsha Pond Main Basin)
- MEN-18 1 core (Menemsha Pond Main Basin)
- MEN-19/20 2 cores (Menemsha Pond Main Basin)
- MEN-21 1 core (Menemsha Pond Channel)
- MEN-22 1 core (Menemsha Pond Main Basin)
- MEN-23 1 core (Menemsha Pond Main Basin)
- MEN-24 1 core (Menemsha Pond Main Basin)

Squibnocket Pond - Brackish

- SQB-1 1 core (Main Basin - North)
- SQB-2 1 core (Main Basin - North)
- SQB-3 1 core (Main Basin - North)
- SQB-4 1 core (Main Basin - North)
- SQB-5 1 core (Main basin - West)
- SQB-6 1 core (Main Basin - South)
- SQB-7 1 core (Main Basin - South)
- SQB-8 1 core (Main Basin - South)
- SQB-9 1 core (Main Basin - North)
- SQB-10 1 core (Main Basin - North)
- SQB-11/12 2 cores (Main Basin - East)
- SQB-13 1 core (Main Basin - East)
- SQB-14 1 core (Main Basin - East)
- SQB-15/16 2 cores (Main Basin - East)

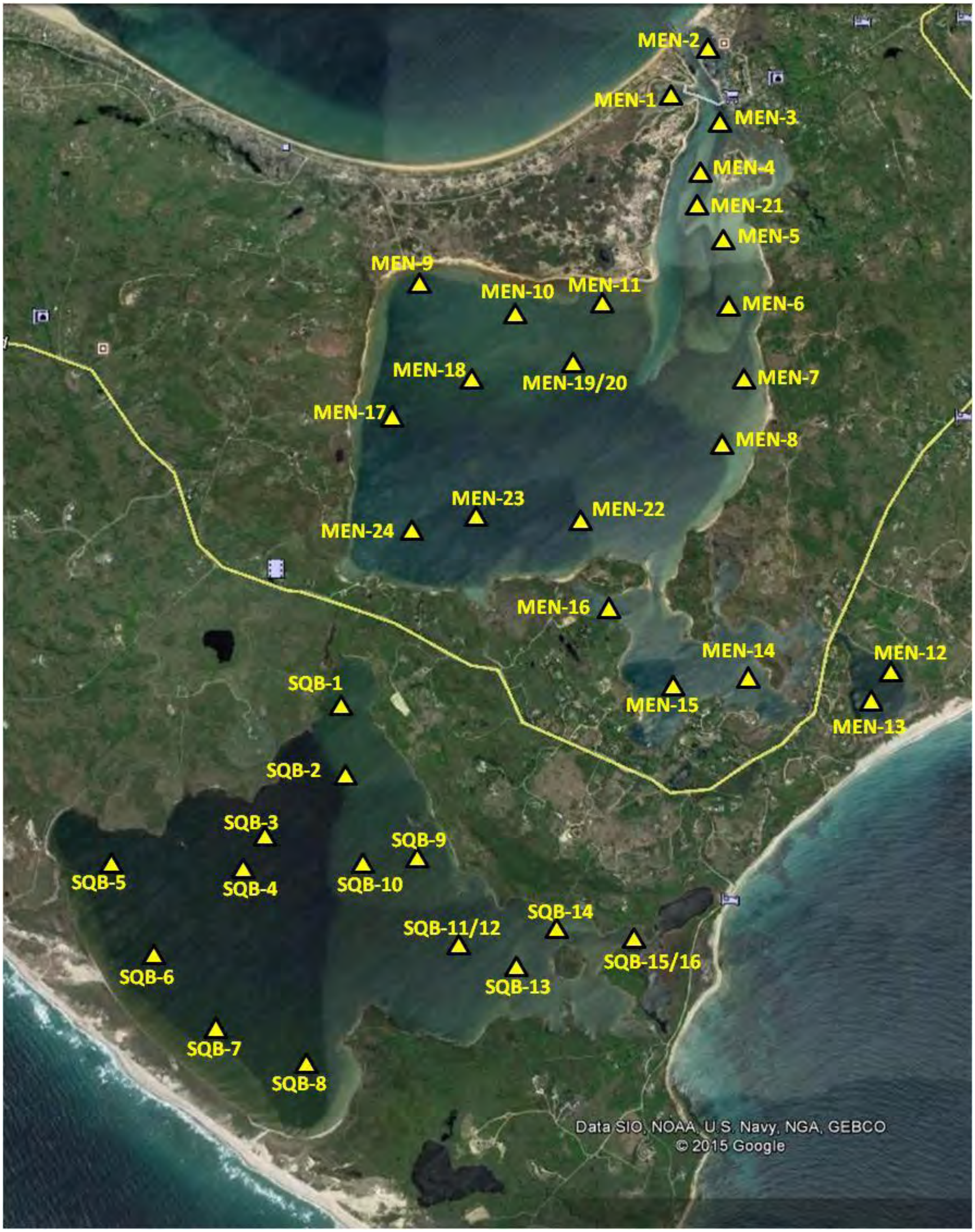

Figure IV-12. Menemsha-Squibnocket Pond Embayment System sediment sampling sites (yellow symbols) for determination of sediment-water column exchange rates. Numbers are for reference to station identifications listed below and in Table IV-5.

Sampling was distributed throughout the primary component basins of the Menemsha-Squibnocket Pond Embayment System (e.g. Menemsha Pond, Nashaquitsa Pond, Stonewall Pond and Squibnocket Pond) and the results were used 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 at the Aquinnah Wampanoag Tribe's station on the southern shore of Menemsha Pond, the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers positioned, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and ortho-phosphate (Murphy and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-20^{o}C) for assay of nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON (D'Elia *et al.* 1977). Rates were determined from linear regression of analyte concentrations through time.

Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA (Coastal Systems Analytical Facility, 508-910-6325 or ssampieri@umassd.edu). The laboratory follows standard methods for saltwater analysis and sediment biogeochemistry.

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 estuarine sediments most denitrification in sediments occurs as settled organic particles decompose and released ammonium is oxidized to nitrate. Some of this nitrate "escapes" to the overlying water and some is denitrified within the sediment column. Both pathways of denitrification are at work within the Menemsha-Squibnocket Pond System.

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 the 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-13).

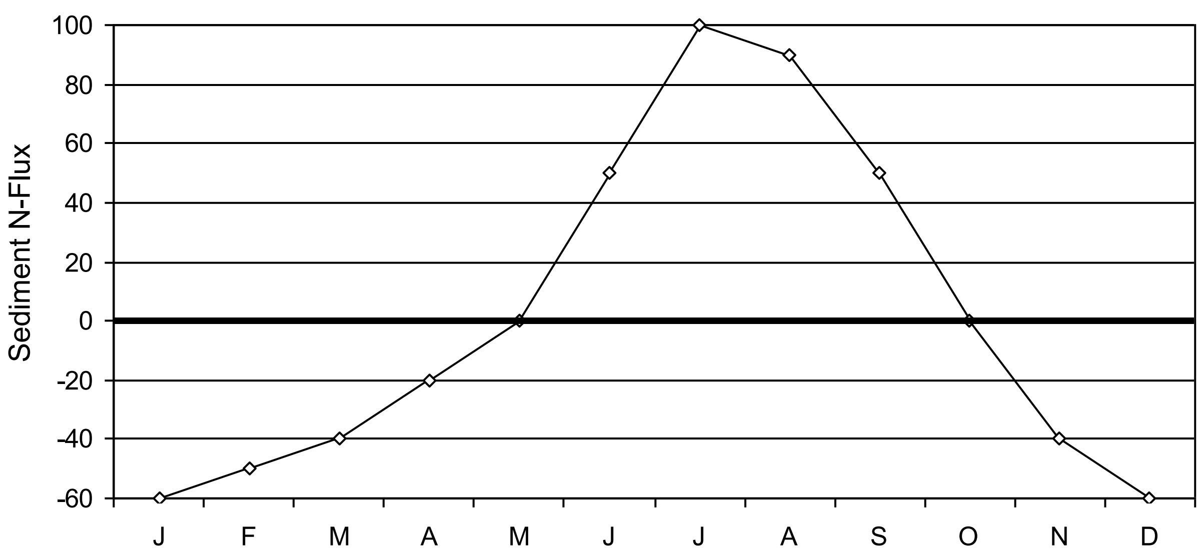

Figure IV-13. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

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

Sediment sampling was conducted throughout the primary component basins of Menemsha Pond (Menemsha Creek/Channel, Nashaquitsa Pond and Stonewall Pond) and in Squibnocket Pond, which comprise the overall embayment system in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores in each basin was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (Section V). Generally 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. However, in the relatively small areas of very high velocity near inlets or main tidal channels or areas of swept sands, a further reduction in deposition is applied. Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas which are net nitrogen sinks for the aquatic system. This approach has been previously validated in outer Cape Cod embayments (Town of Chatham embayments) by examining the relative fraction of the sediment carbon turnover (total sediment metabolism), which would be accounted for by daily particulate carbon settling. This analysis indicated that sediment metabolism in the highly organic rich sediments of the wetlands and depositional basins is driven primarily by stored organic matter (ca. 90%). Also, in the more open lower portions of larger embayments, storage appears to be low and a large proportion of the daily carbon requirement in summer is met by particle settling (approximately 33% to 67%). This range of values and their distribution is consistent with ecological theory and field data from shallow embayments. Additional, validation has been conducted on deep enclosed basins (with little freshwater inflow), where the fluxes can be determined by multiple methods. In this case the rate of sediment regeneration determined from incubations was comparable to that determined from whole system balance.

Net nitrogen release or uptake from the sediments within the embayment basins of the Menemsha-Squibnocket Pond Embayment System (1432 acres, 580 hectares) were comparable to other similar embayments with similar configuration and flushing rates in southeastern Massachusetts, even though portions of this system (e.g. Squibnocket Pond) have very limited tidal flushing. There was a clear pattern of sediment N flux, with higher nitrogen release in the strongly depositional areas (low velocities and deeper water) and high phytoplankton biomass. Overall, the sediments were generally in balance with relatively low net nitrogen release being only slightly positive. The deeper region of the main basin of Menemsha Pond had the highest nitrogen release (8.1 mg N m^{-2} d^{-1}) and most organic sediments, while the shallow areas of the main basin, Nashaquitsa and Stonewall Ponds and Squibnocket Pond showed lower and generally similar rates (-0.5 mg N m^{-2} d^{-1} to 3.3 mg N m^{-2} d^{-1}) The high velocity Menemsha Creek/Channel had typically low rates as seen in sandy high velocity areas (0.7 mg N m^{-2} d^{-1}), similar to areas in the open water basin of Barnstable Great Marshes (mouth of Scorton and Spring Creeks, 2.6-2.5 mg N m^{-2} d^{-1}) and the high velocity oxidized sandy sediments of Chatham Harbor (-8.8 mg N m^{-2} d^{-1}). The well flushed large basin of Menemsha Pond (8.1 mg N m^{-2} d^{-1}) is similar to the open basin of Madaket Harbor on Nantucket and similarly structured Little Pleasant Bay, both of which also have extensive eelgrass (6 mg N m^{-2} d^{-1} and -1.1 to 4.1 mg N m^{-2} d^{-1}, respectively) as well as the large main basin of nearby Tisbury Great Pond (8.8 mg N m^{-2} d^{-1}). The Tisbury Great Pond tributary coves of Pear Tree Cove, Tiah Cove and Deep Bottom/Thumb Cove, with rates of 0.1 mg N m^{-2} d^{-1}, -1.6 mg N m^{-2} d^{-1}, and 6.5 mg N m^{-2} d^{-1}, respectively, were similar to Nashaquitsa and Stonewall Ponds, tributary to Menemsha Pond. These tributary basins in both systems support similar sediments mainly comprised of soft consolidated mud with an oxidized surface layer generally to ~1 cm depth and do not have microbial mats and accumulations of drift macroalgae. The large brackish basin of Squibnocket Pond had low rates of sediment nitrogen release,1.4 mg N m^{-2} d^{-1}, consistent with the Menemsha Pond observed rates.

The other large basins in southeastern Massachusetts have similar rates to those in the Menemsha-Squibnocket Embayment System. For example in the Lewis Bay System the main basin (also a lagoon) averaged 6.9 mg N M^{-2} d^{-1} and the similarly configured West Bay (Three Bays, Barnstable) 4.5 mg N m^{-2} d^{-1}. Based upon the pattern and rate of net nitrogen uptake/release from the sediments in the major basins of Menemsha-Squibnocket Embayment System and the comparable rates in analogous basins in other estuaries throughout the region, the measured rates were used in the water quality modeling effort (Section VI).

The sediments within the Menemsha-Squibnocket Embayment System appear to be in balance with the overlying waters and the nitrogen flux rates are consistent with the level of nitrogen loading to this system and the level of tidal flushing. Net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the Menemsha-Squibnocket Embayment System (Section VI) are presented in Table IV-7. There was a clear spatial pattern of sediment nitrogen flux with the magnitude and pattern of sediment nitrogen release being consistent with the distribution of sediment types and deposition rates and is consistent with other similarly structured estuaries with low to moderate watershed nitrogen loading.

Table IV-7. Rates of net nitrogen return from sediments to the overlying waters of the Menemsha-Squibnocket Pond Embayment System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (Section VI). Measurements represent July - August rates. Note that Squibnocket Pond is brackish water.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			Sta. i.d. *
	Mean	S.E.	# sites	
Menemsha Pond				
Menemsha Creek	0.7	1.5	5	MEN 1,2,4,5,21
Menemsha Main Basin	8.1	7.2	13	MEN 6-11,17-20,23,24
Nashaquitsa Pond	3.3	14.7	3	MEN 14,15,16
Stonewall Pond	-0.5	10.7	2	MEN 12,13
Squibnocket Pond				
Squibnocket Pond	1.4	5.6	16	SQB 1-16

* Station numbers refer to Figure IV-12.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This hydrodynamic study was performed for the Menemsha-Squibnocket Pond Embayment System, located on the boundary between Aquinnah and Chilmark, Massachusetts, at the southwest corner of Martha's Vineyard. A topographic map detail in Figure V-1 shows the general study area. Menemsha Pond is an estuarine system with a jettied inlet that opens to Vineyard Sound. The inlet channel (Menemsha Creek) is a federally authorized channel, which is maintained by the US Army Corps of Engineers (USACE). Two sub-embayments are connected to the main basin of Menemsha Pond: Squibnocket Pond and Nashaquitsa Pond (+Stonewall Pond). The lowest elevations of the system exist in the inlet channel and the main basin of Menemsha Pond, where maximum depths are approximately -25 ft NAVD. The total surface coverage of the whole estuary, including its sub-embayments is approximately 1,460 total acres,

Tidal exchange with Vineyard Sound dominates circulation in the Pond. From measurements made in the course of this study, the average offshore tide range is 2.9 feet. As indicated by the lack of attenuation of the tide range between Vineyard Sound, Menemsha Basin and Stonewall Pond, tidal flushing appears very efficient throughout the open tidal reaches of the system. Unlike the main portion of the system, tides in Squibnocket Pond are nearly completely attenuated. Squibnocket Pond is connected to Menemsha Pond through Herring Creek, a 1,800-foot long channel with three flow control structures. As a result of the natural and man-made flow restrictions of Herring Creek, water levels in Squibnocket Pond change slowly, on the time scale of days.

The complete hydrodynamic study of the Menemsha-Squibnocket Pond Embayment System was developed from two component efforts. First, bathymetry and tide data were collected in order to accurately characterize the physical system, and to provide data necessary for the modeling portion of the study. Bathymetry surveys of the basins and channels of the Menemsha-Squibnocket Pond Embayment System were performed to determine the variation of depths throughout the main tidal creeks. A 2013 USACE survey of Menemsha Creek and Basin supplemented more recent 2015 surveys of Menemsha Pond (including Stonewall Pond) and Squibnocket Pond. In addition to the bathymetry survey, tides were recorded at five stations for a month-long period, and ADCP velocity measurements were collected at the Creek inlet. These tides and ADCP data were necessary to run, calibrate and corroborate the hydrodynamic model of the system.

A numerical hydrodynamic model of the Menemsha-Squibnocket Pond Embayment System and its attached sub-embayments was developed in the second portion of this study. Using the bathymetry survey data, a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data collected offshore in Vineyard Sound were used to define the open boundary condition that drives the circulation of the model. Data measured within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the real, physical system.

The calibrated hydrodynamic model of Menemsha Pond and Squibnocket Pond is an integral piece of the water quality model developed in the next Section of this report. In addition to its use as the hydrodynamic basis for the TN and salinity models, the calibrated hydrodynamic model is a useful tool that can be used to investigate the tidal properties of the system.

Figure V-1. Topographic map detail of the Menemsha-Squibnocket Pond Embayment System.

V.2 DATA COLLECTION AND ANALYSIS

The field data collection portion of this study was performed to characterize the physical properties of the Menemsha-Squibnocket Pond Embayment System. Bathymetry data were collected throughout the system so that it could be accurately represented as a computer hydrodynamic model and flushing rates could be determined for the system. In addition to the bathymetry, tide elevation and ADCP velocity data were also collected in the system (including Squibnocket Pond), in order to run the circulation model with real tides, and also to calibrate and corroborate its performance.

V.2.1 Bathymetry Data

A bathymetric survey of the Menemsha-Squibnocket Pond Embayment System was performed by SMAST in November 2015. This data set was supplemented with detailed bathymetry of Menemsha Creek, measured by the USACE in 2013. The actual survey paths followed by the survey craft during both surveys are shown in Figure V-2. The NOAA GEODAS data archive was used to as a source of bathymetry data for offshore areas in Vineyard Sound not covered in either the 2013 or 2015 surveys.

The resulting bathymetric surface created by interpolating the data to a finite element mesh is shown in Figure V-3. All soundings were tide corrected using tide data collected in the Pond. The data were all rectified to the NAVD 88 vertical datum.

Results from the survey show that the deepest point in the Menemsha Pond portion of the system is located in Menemsha Creek, at the inlet channel, though nearly equal depths were measured in Menemsha Pond basin itself. The deepest depth measured in the course of the 2013 USACE survey is -27.3 feet NAVD. The deepest measurement in the Menemsha Pond basin in the 2015 SMAST survey was -26.3 feet NAVD. Generally, the average depth of the whole system is moderately deep, with a mean depth of -8.9 feet NAVD.

V.2.2 Tide Data Collection and Analysis

Tide data records were collected concurrently at three gauging stations located in Vineyard Sound (Menemsha Bight, MP1), at Menemsha Basin (MP2), Menemsha Pond at Herring Creek (MP3), in Stonewall Pond (MP4) and Squibnocket Pond (MP5). The Temperature Depth Recorders (TDR) used to record the tide data were deployed for an overlapping 39-day period between October 15 and November 23, 2015. The elevation of each gauge was surveyed relative to the NAVD vertical datum. The Vineyard Sound tide record was used as the open boundary condition of the hydrodynamic model. Data from inside the system were used to calibrate the model.

Tide records longer than 29 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.

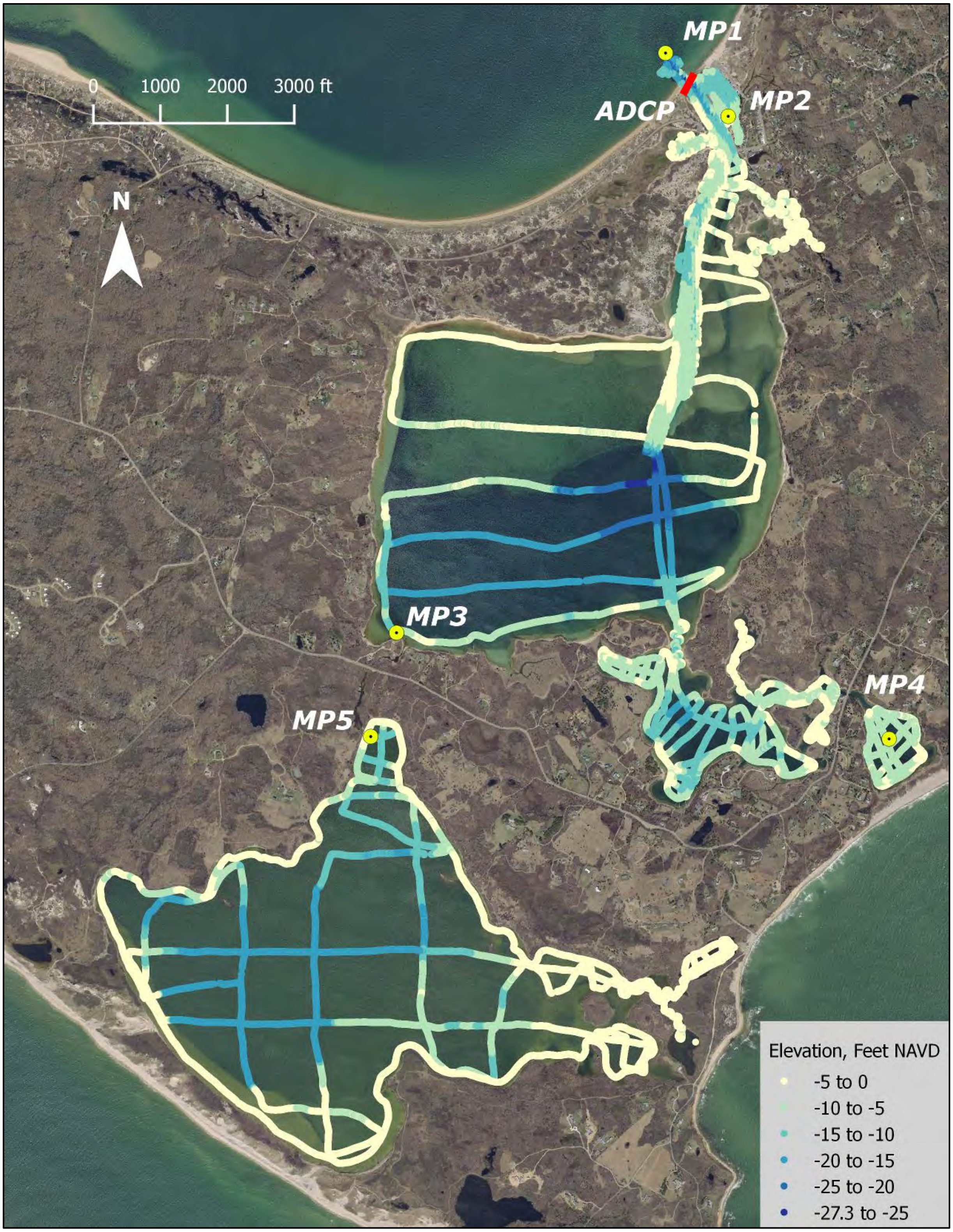

Figure V-2. Boat lines from the 2013 USACE and 2015 SMAST bathymetry surveys of the Menemsha-Squibnocket Pond Embayment System. Yellow markers show the locations of the tide recorders deployed for this study. The cross-channel transect followed during the ADCP survey of tidal velocities (at the inlet) is indicated using the solid red line.

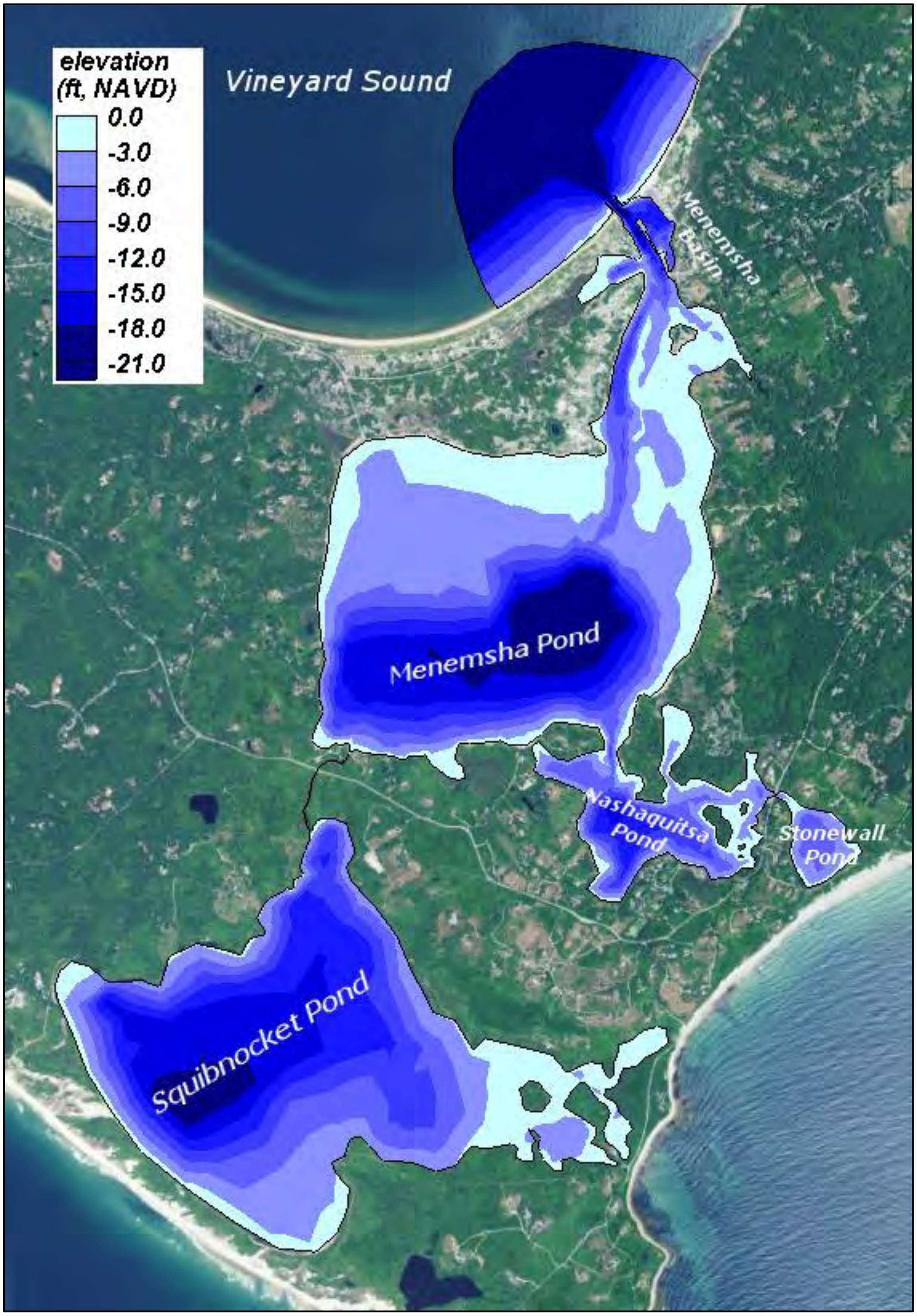

Figure V-3. Bathymetry data interpolated to the finite element mesh used with the RMA-2 hydrodynamic model. Contours represent the bottom elevation relative to mean low water (NAVD). The primary data source used to develop the grid mesh is the November 2015 survey of the main basins of system, supplemented by the 2013 USACE survey of Menemsha Creek, and NOAA GEODAS data used for the offshore area in Vineyard Sound.

Plots of the tide data from the five gauges are shown in Figure V-4 for the overlapping 39-day of the gauge deployment. The spring-to-neap variation in tide range is discernable in these plots. A period of spring tides occurs around the full moon October 27, where the maximum range in the record is approximately 5 feet. A week later there is a period of neap tides, where the minimum range of 2 feet occurs on November 4, the day of the waning half-moon. Following this neap tide is a continuing cycle of neap and spring tides, though the transition is more muted than at the beginning of the month. The visual comparison between tide elevations offshore and at the different stations in the system shows that the tide amplitude does not change much, even in the inner-most unobstructed reaches (not considering Squibnocket Pond) of the system at Stonewell Pond.

V.2.2.a Tide Datums

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 39-day records. These datums are presented in Table V-1. For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data were available; however, these datums still provide a useful comparison of tidal dynamics within the system. The Mean Higher High (MHH) and Mean Lower Low (MLL) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW.

Table V-1. Tide datums computed from 39-day records collected offshore and in the Menemsha-Squibnocket Pond Embayment System in October and November 2015. Datum elevations are given relative to NAVD vertical datum. Water levels in Squibnocket Pond do not vary tidally, and only minimum and maximum water levels during the gauge deployment period are provided.

Tide Datum	Vineyard Sound (feet)	Menemsha Basin (feet)	Menemsha Pond (feet)	Stonewall Pond (feet)	Squibnocket Pond (feet)
Maximum Tide	3.6	3.6	3.5	3.5	0.9
MHHW	2.0	2.2	2.1	2.1	-
MHW	1.8	2.0	1.9	1.9	-
MTL	0.3	0.5	0.4	0.5	-
MLW	-1.2	-1.0	-1.0	-1.0	-
MLLW	-1.3	-1.1	-1.1	-1.1	-
Minimum Tide	-2.3	-2.2	-1.8	-1.7	0.2
Mean Range	3.0	2.9	2.9	2.9	-

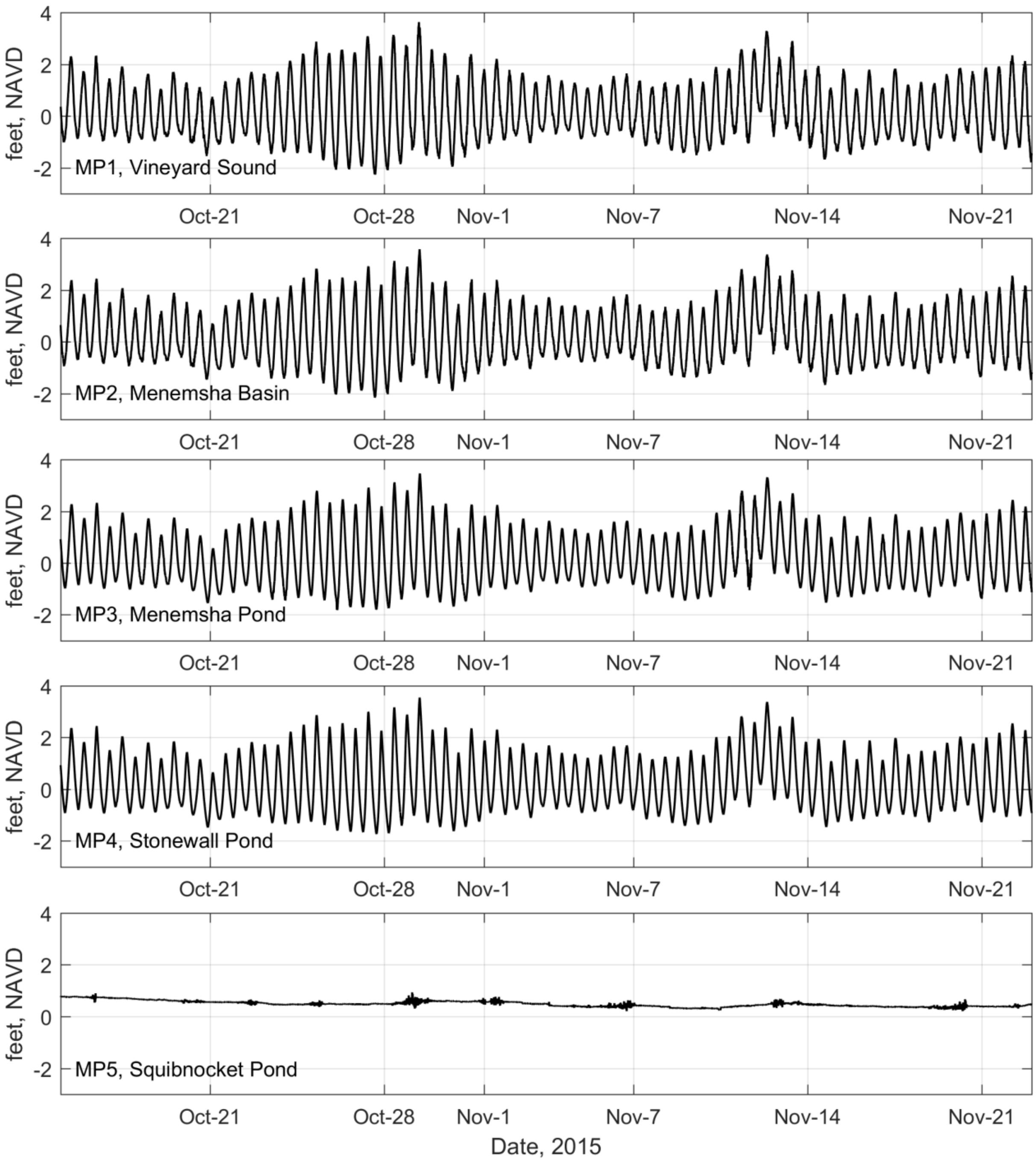

Figure V-4. Plots of observed tides for stations in the Menemsha-Squibnocket Pond Embayment system, for the overlapping 41-day period between October 15 and November 23, 2015 the gauges were all recording. All water levels are referenced to the NAVD vertical datum.

Little frictional damping occurs in this system. The mean tide range at all three stations within Menemsha Pond is within ±0.1 feet. The two-day period of tides in Figure V-5 shows that though there is little change in the elevation of high and low tides in the main estuarine reach of the system through to Stonewall Pond, there is an obvious delay in the timing of the tide which increases from the system inlet to the uppermost reaches.

V.2.2.b Tide Harmonic Analysis

In addition to the calculation of tide datums for the gauge records, a harmonic analysis of the tidal time series was also performed to produce tidal amplitude and phase of the major tidal constituents, and provide assessments of hydrodynamic ‘efficiency’ of the system in terms of tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each system.

Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The observed astronomical tide the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents computed for the Menemsha Pond gauge data add together is shown in Figure V-6. The amplitudes and phase of 21 known tidal constituents result from this procedure. Table V-2 presents the amplitudes of seven tidal constituents computed for the four Menemsha Pond system records that are tidal. The M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an offshore amplitude of 1.4 feet. The total range of the offshore M_2 tide is twice the amplitude, or 2.8 feet.

Table V-2. Tidal Constituents computed for tide stations in the Menemsha Pond system during October and November 2015.

	Amplitude (feet)						
Constituent	M_2	M_4	M_6	S_2	N_2	K_1	O_1
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82
Vineyard Sound	1.41	0.17	0.03	0.36	0.38	0.18	0.14
Menemsha Basin	1.36	0.14	0.05	0.30	0.35	0.18	0.14
Menemsha Pond	1.34	0.17	0.04	0.27	0.33	0.18	0.14
Stonewall Pond	1.32	0.20	0.05	0.27	0.33	0.18	0.15

The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.2 feet and 0.1 feet respectively. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, also contribute to the total tide signal, both with amplitudes of 0.4. The M_4 and M_6 tides are higher frequency harmonics of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water.

Generally, it can be seen that as the total tide range is the same through the system, the amplitude of the individual tide constituents remains about the same also. This is true even of the M_4 and M_6 overtide amplitudes, which indicate little energy loss due to tidal damping of the M_2. The amplitude of the M_2 decreases less than 0.1 feet between Vineyard Sound and Stonewall Pond.

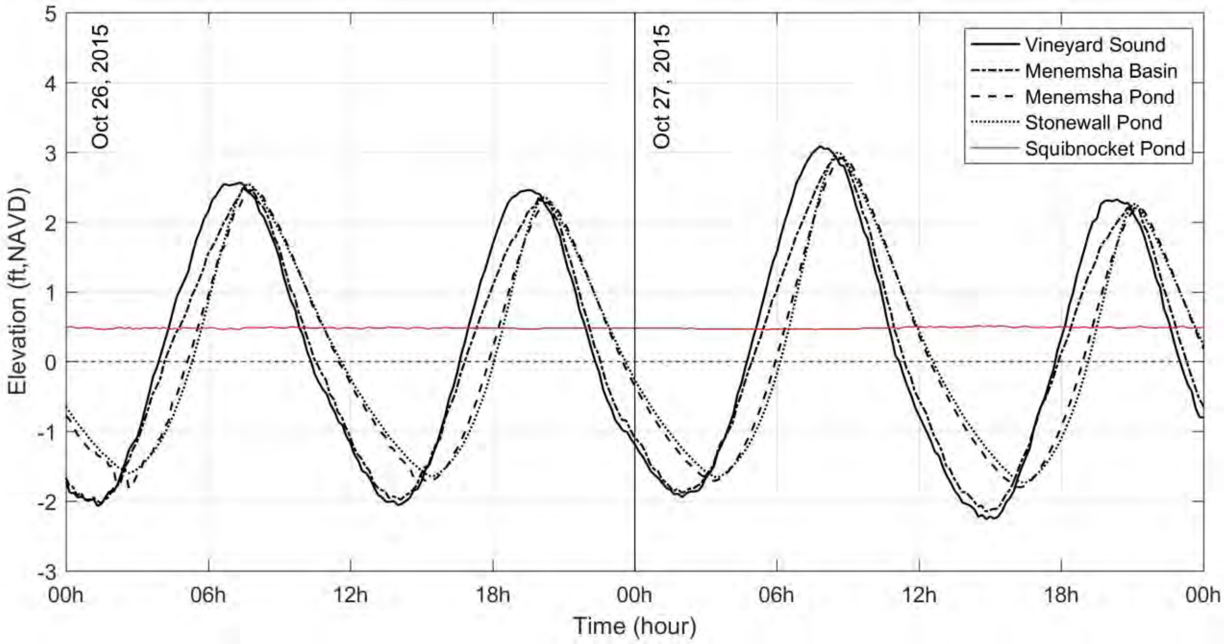

Figure V-5. Two-day tide plot showing tides measured at stations in the Menemsha-Squibnocket Pond Embayment system.

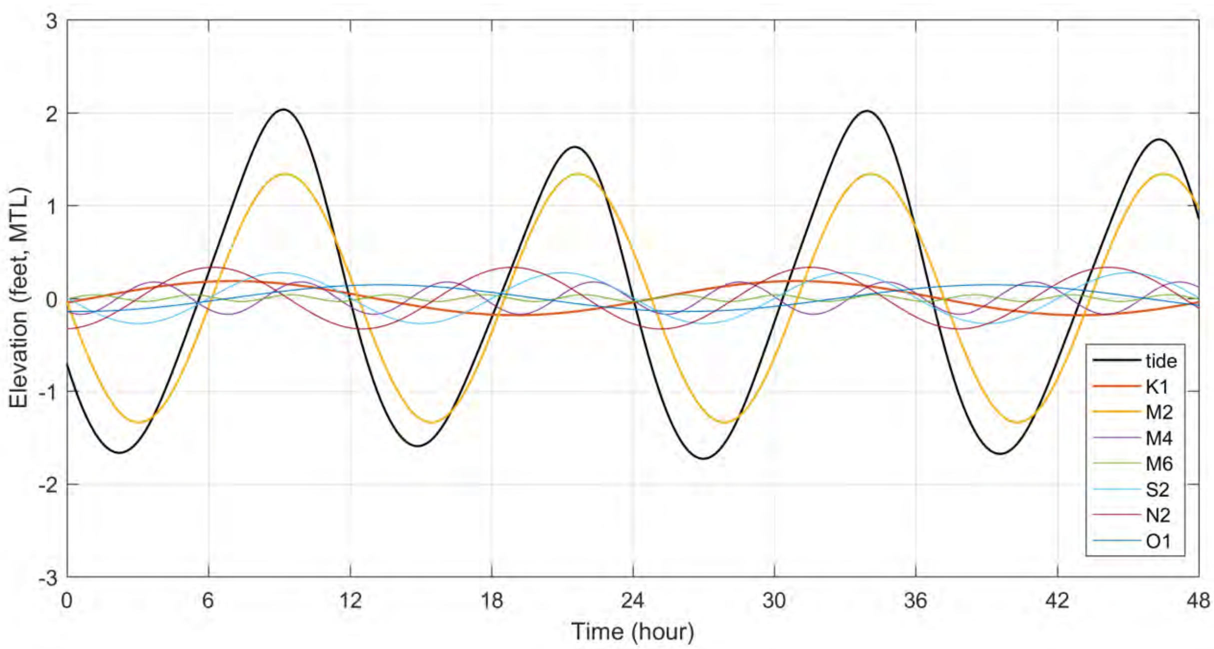

Figure V-6. Example of an observed astronomical tide as the sum of its primary constituents, using tide constuituents computed for the Menemsha Pond gauge (MP3).

Although constituent amplitudes across the system and its sub-embayments remain relatively consistent, the timing of the tides through the system does change, which results from the time it takes the tide to propagate through to the upper reaches of the system. Table V-3 shows the delay of the M_2 at different points in the Menemsha-Squibnocket Pond Embayment system, relative to the timing of the M_2 constituent in Vineyard Sound. At Menemsha Basin, just inside the inlet, the measured delay (about 4 minutes) of the M_2 is less than the time step of the data record (10 minutes). This indicates that the phasing of the tides is essentially the same, and that there is no significant phase delay across the inlet. Farther in the system, at the discharge of Herring Creek into Menemsha Pond and at Stonewall Pond, the delay is as much as 46 minutes.

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

The results of an analysis to determine the energy distribution (or variance) of the measured water elevation records for the gauge records in the Menemsha-Squibnocket Pond Embayment System compared to the energy content the astronomical tidal signal (re-created by summing the contributions from the 21 constituents determined by the harmonic analysis) is presented in Table V-3. Subtracting the tidal signal from the original elevation time series yielded 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 generates a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from the tide gauge in Menemsha Pond at Herring Creek (MP3), with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

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

Station	Delay (minutes)
Menemsha Basin	5.7
Menemsha Pond	40.5
Stonewall Pond	46.2

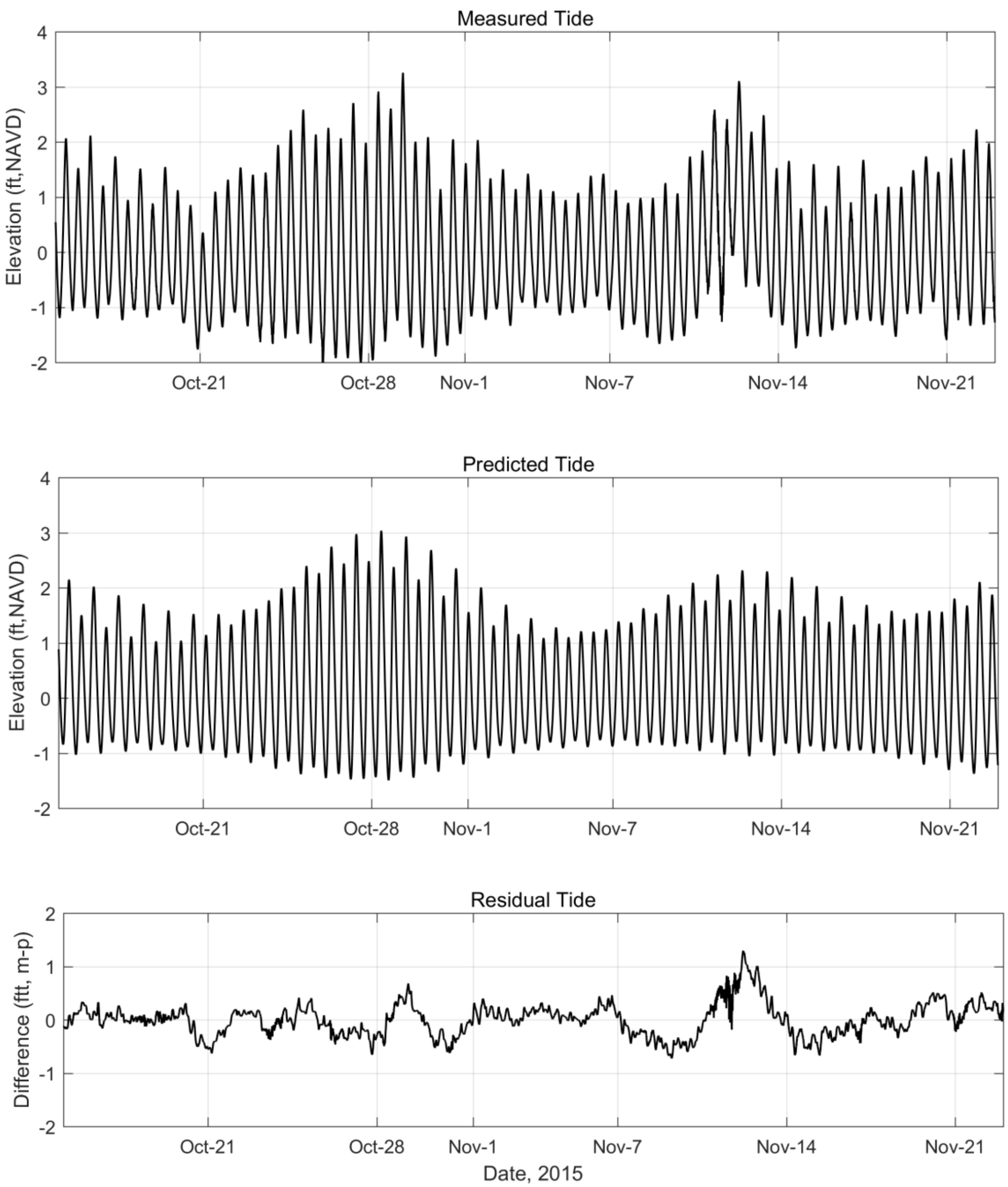

Figure V-7. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 21 individual tide constituents determine in the harmonic analysis of the Menemsha Pond (MP3, at Herring Creek) gauge data. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (r=m-p).

Table V-4 shows that the variance of tidal energy is practically the same at all three gauging stations inside the system inlet (excluding Squibnocket Pond, which is not tidal), and that the tidal contribution to the total variance is the same percentage (approximately 91 percent) at these three stations as well. Though there are some larger deviations between the measured and astronomical tide records, the mean non-tidal variance of the complete records at each station indicate that non-tidal effects on the total observed water level changes are not a large contributor to the total measured tide, on average.

Table V-4. Percentages of Tidal versus Non-Tidal Energy for stations in the Menemsha Pond system and Vineyard Sound, October to November 2015.

TDR Location	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Vineyard Sound	1.2	93.4	6.6
Menemsha Basin	1.1	91.3	8.7
Menemsha Pond	1.1	91.8	8.2
Stonewall Pond	1.1	91.4	8.6

V.2.2.b Tide Flood and Ebb Dominance

An investigation of the flood or ebb dominance of different areas in the Menemsha-Squibnocket Pond Embayment System was performed using the measured tide data. Estuaries and sub-embayments that are flood dominant are typically areas that collect sediment over time since they have maximum flood tide velocities that are greater than the maximum velocities that occur during the ebb portion of the tide. Salt marshes tend to be flood dominant, as this condition allows them to collect material that is required to maintain healthy marsh resources.

Flood or ebb dominance in channels of a tidal system can be determined by utilizing the results of the harmonic analysis of tidal elevations, or by performing a similar analysis on a time series of tidal currents. A discussion of the method of relative phase determination is presented in Friedrichs and Aubrey (1988). For this method, the same M_2 and M_4 tidal constituents presented in Table V-2 were used as the basis of this analysis.

For constituents based on tidal elevations, the relative phase difference is computed as the difference between two times the M_2 phase and the phase of the M_4, expressed as $\Phi=2M_2-M_4$. If Φ is between 0 and 180 degrees ($0<\Phi<180$), then the channel is characterized as being flood dominant, and peak flood velocities will be greater than for peak ebb. Alternately, if Φ were between 180 and 360 degrees ($180<\Phi<360$), then the channel would be ebb dominant. If Φ is exactly 0 or 180 degrees, neither flood nor ebb dominance occurs. For Φ equal to exactly 90 or 270 degrees, maximum tidal distortion occurs and the velocity residuals of a channel are greatest. This relative phase relationship is presented graphically in Figure V-8.

Though this method of tidal constituent analysis provides similar results to a visual inspection of a tidal record (e.g., by comparing peak ebb and flood velocities), it allows a more exact characterization of the tidal processes. By this analysis technique, a channel can be characterized as being strongly, moderately, or weakly flood or ebb dominant.

The five gauge stations in the system were used for this analysis. These data make it possible to characterize the flood or ebb dominance of different areas of the system from offshore (MP1 in Vineyard Sound) through to the upper reaches of the system (e.g., WP4, in Stonewall Pond). The results of this velocity analysis of the Menemsha Pond measured tide data show that the system, including the offshore are characteristically flood dominant by varying degrees. The computed values of $2M_2$-M_4 are presented in Table V-5. Menemsha Basin is only weakly flood dominant, and the inner basins of the system that are tidal (e.g., Menemsha Pond and Stonewall Pond) show a stronger level of flood dominance than the offshore region.

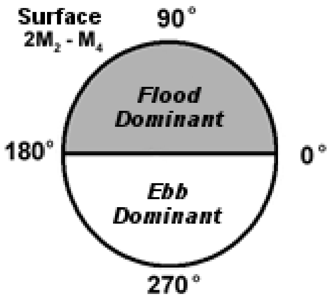

Figure V-8.Relative velocity phase relationship of M2 and M4 tidal elevation constituents and characteristic dominance, indicated on the unit circle. Relative phase is computed as the difference of two times the M2 phase and the M4 phase (2M2-M4). A relative phase of exactly 90 or 270 degrees indicates a symmetric tide, which is neither flood nor ebb dominant.

Table V-5. Menemsha Pond system relative tidal phase differences of M_2 and M_4 tide constituents, determined using tide elevation record records in areas of the system that are tidal.

location	$2M_2$-M_4 relative phase (deg)	Characteristic dominance
Vineyard Sound	23.7	Moderate Flood
Menemsha Basin	5.9	Weak Flood
Menemsha Pond	35.7	Moderate Flood
Stonewall Pond	39.0	Moderate Flood

V.3 HYDRODYNAMIC MODELING

For the modeling of the Menemsha-Squibnocket Pond Embayment System, Applied Coastal utilized a computer hydrodynamic model to evaluate tidal circulation and flushing in the Pond. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2 for numerous flushing studies on Cape Cod, including West Falmouth Harbor, Popponesset Bay, Chatham embayments (Kelley, *et al*, 2001), Falmouth "finger" Ponds (Howes *et al*, 2005), Three Bays (Kelley *et al*, 2003) and Barnstable Harbor (Howes, *et al*, 2017).

V.3.1 Model Theory

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report primarily were generated within the SMS modeling package.

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

The extent of each finite element grid was generated using 2014 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of Menemsha Creek based on the tide gauge data collected offshore in Vineyard Sound. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several model calibration simulations for the system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. Mass GIS 2014 digital aerial orthophotos and the 2013 USACE and 2015 SMAST bathymetry survey data were imported to SMS, and a finite element grid was generated to represent the estuary. The aerial photography was used to determine the land boundary of the system. The bathymetry data were interpolated to the developed finite element mesh of the system. The completed grid consists of 6,096 nodes, which describe 2,744 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth inside the estuarine portion of the grid (i.e., not including the offshore area is -25.1 ft (NAVD). The completed grid mesh of the Menemsha-Squibnocket Pond Embayment System is shown in Figure V-9.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Menemsha Pond and its attached subembayments. Areas of marsh were included in the model because they represent a significant portion of the total surface area of this system. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Grid resolution is generally governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution is employed where complex flow patterns are expected, generally near the inlet. Appropriate implementation of wider node spacing and larger elements reduces computer run time with no sacrifice of accuracy.

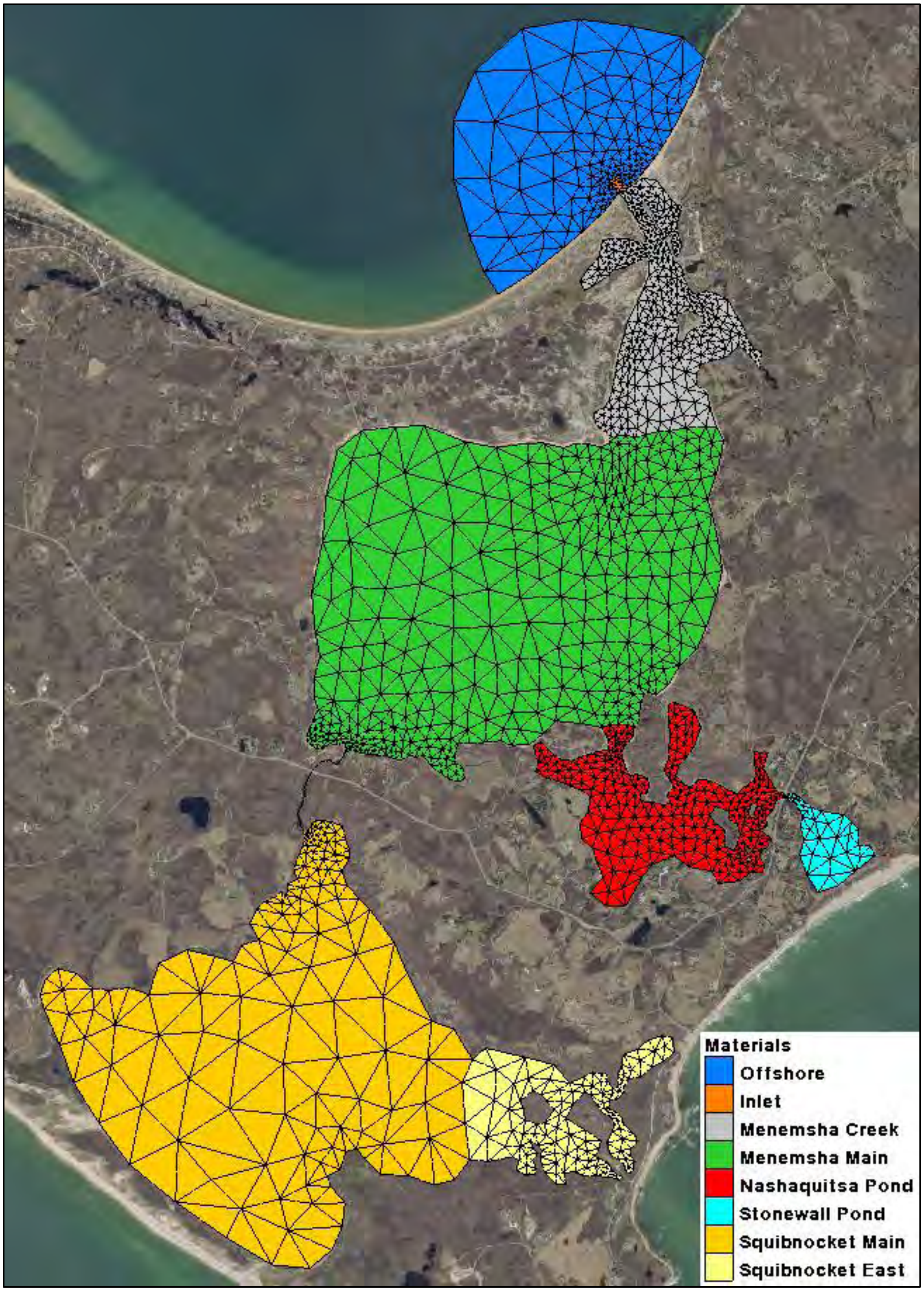

Figure V-9. Plot of hydrodynamic model grid mesh for the Menemsha-Squibnocket Pond Embayment System. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

V.3.2.2 Boundary condition specification

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

V.3.2.3 Calibration

After developing the finite element grids, and specifying boundary conditions, the model for the Menemsha-Squibnocket Pond Embayment System was calibrated. The calibration procedure ensures that the model predicts accurately what was observed in nature during the field measurement program. Numerous model simulations are typically required for an estuary model, specifying a range of friction and eddy viscosity coefficients, to calibrate the model.

Calibration of the hydrodynamic model required a close match between the modeled and measured tides from stations inside the system (i.e., from the TDR deployments). Initially, the model was calibrated to obtain visual agreement between modeled and measured tides.

Once visual agreement was achieved, an 8-day period (15 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section V.2. The 8-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibration was performed for the 8-day period beginning October 23, 2015 at 1900 EST. This representative time period included one full cycle between spring and neap periods.

After the model was calibrated, an additional verification run was made in order test the model performance in a time period outside of the calibration period. The model verification was performed by comparing model tidal flowrates at the inlet to flows derived from ADCP measurements during the survey performed November 19, 2015.

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

V.3.2.3.a Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient, and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.022 and 0.055 were specified for all element material types. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels and marsh plains with higher friction (Henderson, 1966).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning's coefficients were matched to bottom type. For example, lower friction coefficients were specified for main basin of Menemsha Pond, versus the shallow and rock-strewn channel of Herring Creek to Squibnocket Pond, which provides greater flow resistance. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992), and values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-6.

Table V-6. Manning's Roughness and eddy viscosity coefficients used in simulations of the Menemsha-Squibnocket Pond Embayment System. These embayment delineations correspond to the material type areas shown in Figure V-8.

System Embayment	bottom friction	eddy viscosity lb-sec/ft^2
Vineyard Sound	0.024	30
Menemsha Creek inlet	0.024	20
Menemsha Creek	0.027	25
Menemsha Pond	0.025	25
Nashaquitsa Pond	0.027	20
Stonewall Pond	0.027	20
State Road bridge at Stonewall Pond	0.035	30
Herring Creek	0.055	60
Squibnocket Pond main basin	0.022	20
Squibnocket Pond east	0.024	20

V.3.2.3.b Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set to 20 lb-sec/ft^2 (Table V-6). A higher value of 60 lb-sec/ft^2 was used for the turbulent channel of Herring Creek.

V.3.2.3.c Comparison of modeled tides and measured tide data

A best-fit of model output for the measured data was achieved using the aforementioned values for friction and turbulent exchange. Figures V-10 through V-14 illustrate sections of the 8-day simulation periods for the calibration model. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the system embayments. Four tidal constituents were selected for constituent comparison: the K_1, M_2, M_4 and M_6. Measured tidal constituent amplitudes are shown in Table V-7. The constituent amplitudes shown in these table differ from those in Table V-2 because constituents were computed for only the shorter sub-sections of the 39-days represented in Table V-2. In Table V-7, error magnitudes are shown for the calibration run.

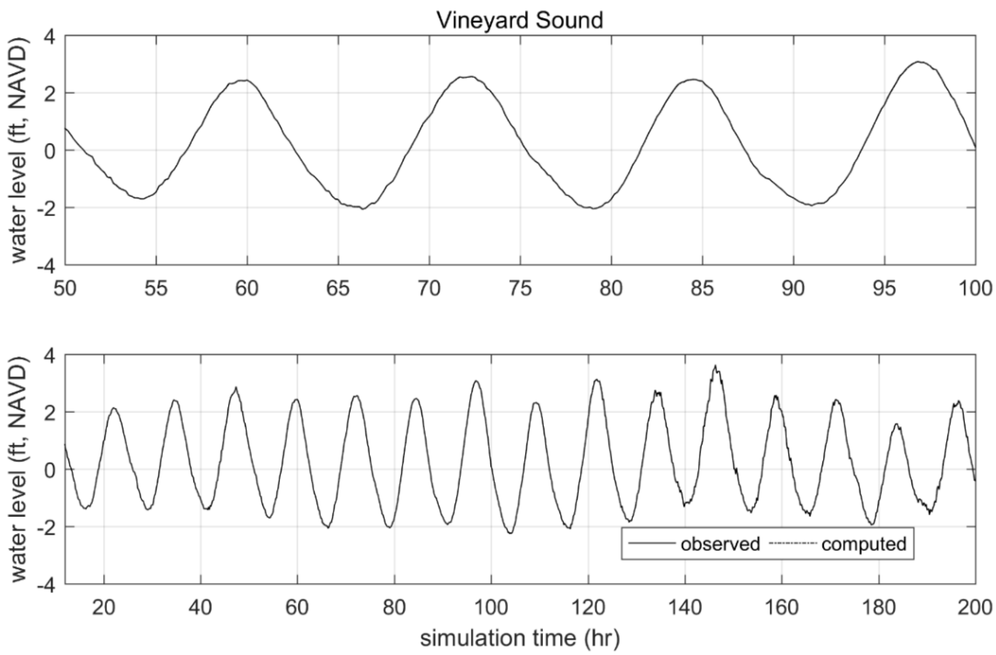

Figure V-10. Comparison of model output and measured tides for the TDR location offshore in Vineyard Sound (MP1) for the final calibration model run (starting October 23, 2014 at 19:00 EST). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

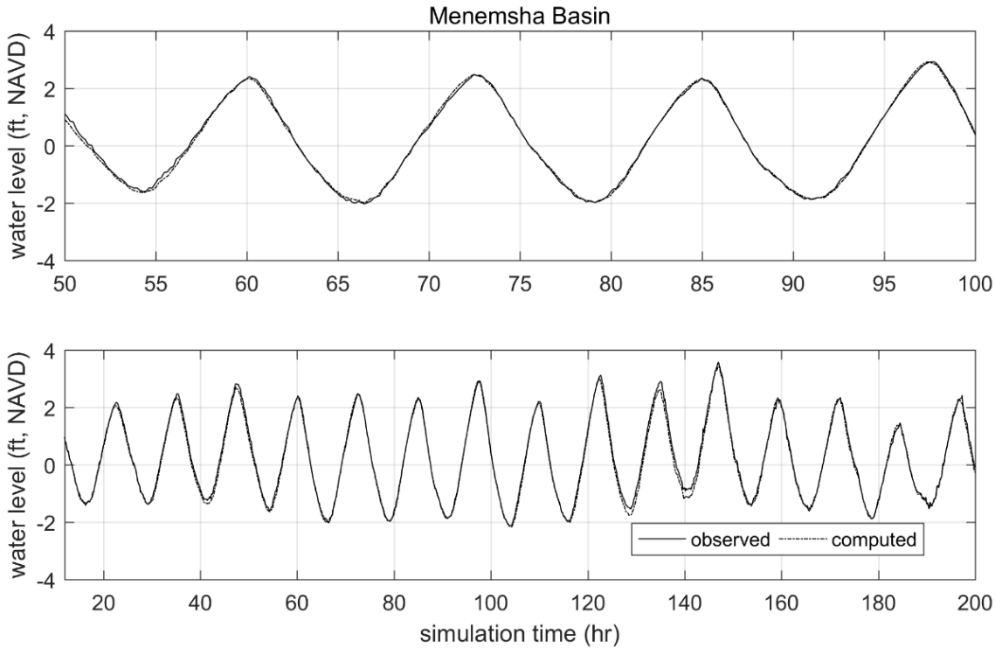

Figure V-11. Comparison of model output and measured tides for the TDR location at Menemsha Basin (MP2) for the final calibration model run (starting October 23, 2014 at 19:00 EST). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

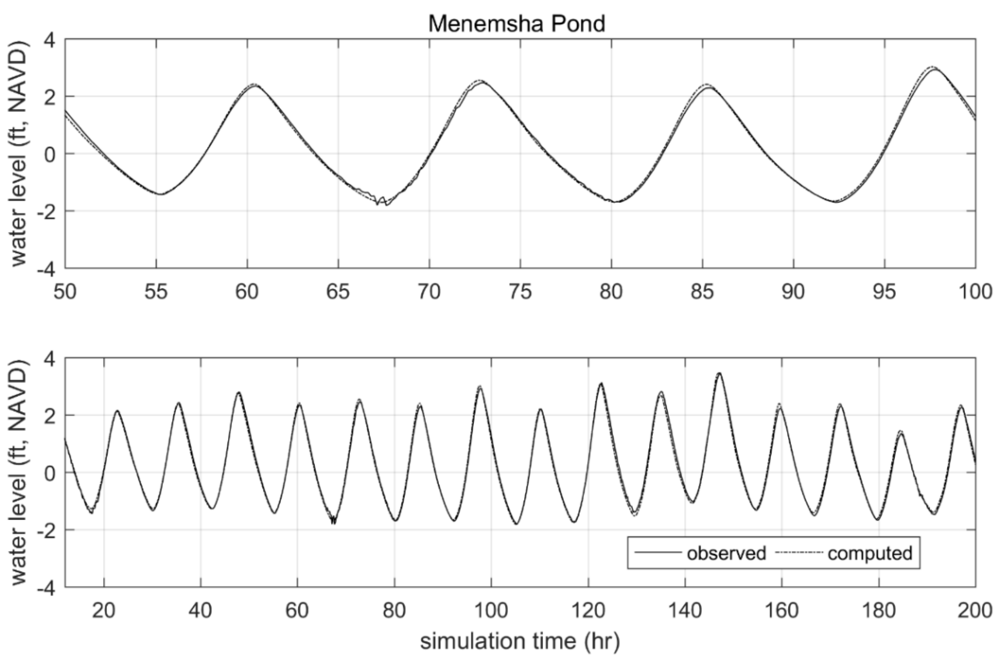

Figure V-12. Comparison of model output and measured tides for the TDR location at Menemsha Pond at Herring Creek (MP3) for the final calibration model run (starting October 23, 2014 at 19:00 EST). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

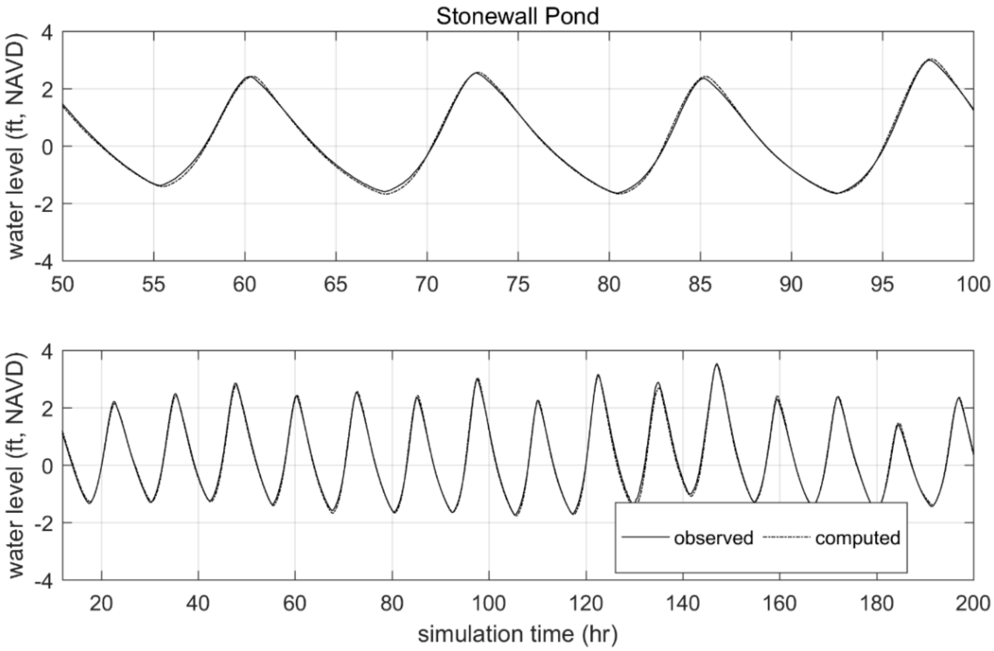

Figure V-13. Comparison of model output and measured tides for the TDR location at Stonewall Pond at (MP4) for the final calibration model run (starting October 23, 2014 at 19:00 EST). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

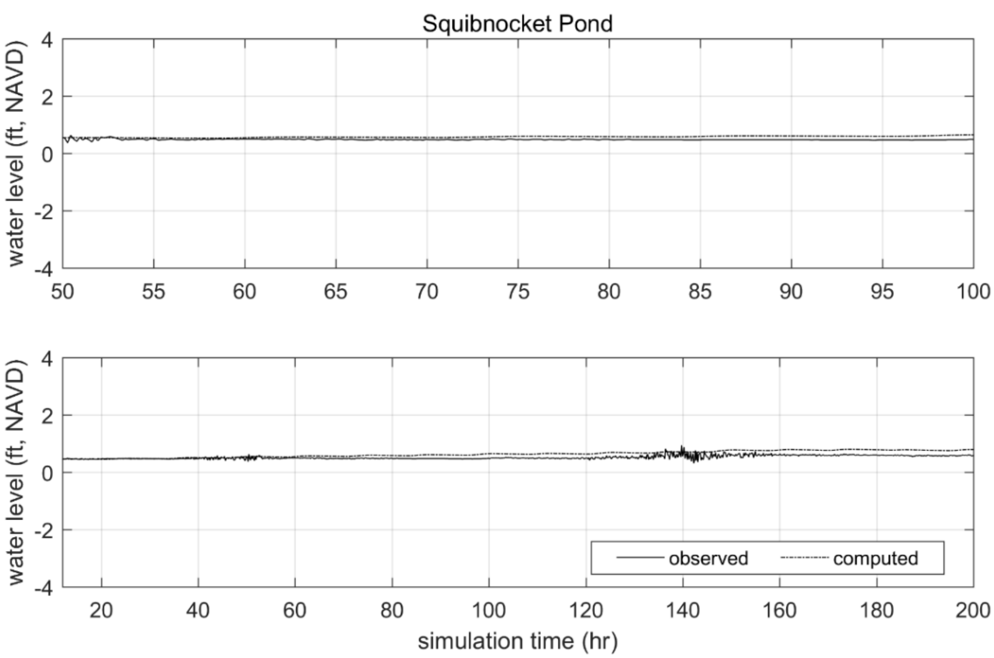

Figure V-14. Comparison of model output and measured tides for the TDR location at Squibnocket Pond at (MP5) for the final calibration model run (starting October 23, 2014 at 19:00 EST). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

Table V-7. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for gauge station in the Menemsha-Squibnocket Pond Embayment System, during modeled calibration time period.						
Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Offshore	2.008	0.239	0.059	0.247	-56.6	-152.5
Menemsha Basin	1.874	0.189	0.100	0.236	-49.3	-117.8
Menemsha Pond	1.786	0.318	0.081	0.236	-19.2	-103.5
Stonewall Pond	1.761	0.353	0.094	0.234	-26.7	-104.1
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Offshore	2.014	0.244	0.059	0.245	-56.5	-152.6
Menemsha Basin	1.877	0.169	0.118	0.233	-49.5	-105.9
Menemsha Pond	1.790	0.295	0.067	0.238	-25.5	-98.4
Stonewall Pond	1.777	0.376	0.075	0.236	-24.4	-98.1
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Offshore	0.006	0.005	0.000	-0.003	0.4	-0.1
Menemsha Basin	0.003	-0.020	0.018	-0.003	-0.3	12.3
Menemsha Pond	0.004	-0.023	-0.014	0.002	7.6	5.3
Stonewall Pond	-0.016	-0.023	0.019	-0.002	-4.7	-6.3

The constituent calibration resulted in excellent agreement between modeled and measured tides for regions that are tidal (Squibnocket is not tidal). The errors associated with tidal constituent amplitude for both the calibration and verification simulations were generally less than 0.01 feet, which is well within the stated accuracy of the tide gages (0.24 ft). Time lag errors for the main estuary reach were less than the time increment resolved by the model and tide data (10 minutes), indicating good agreement between the model and data. The skill of the model calibration is also demonstrated by the high degree of correlation (R^2) and low RMS error shown in Table V-8 for all stations.

Table V-8. Error statistics for the Menemsha Pond hydrodynamic model, for model calibration and verification model runs. Error estimate provided in feet.		
	Calibration	
	R^2	RMS error
Offshore	1.00	0.02
Menemsha Basin	0.99	0.13
Menemsha Pond	0.99	0.12
Stonewall Pond	1.00	0.08
Squibnocket Pond	-	0.14

V.3.2.3.e ADCP corroboration of hydrodynamic model

An additional evaluation of model corroboration with measured data was performed by comparing model flow rates and ADCP field measurements. An ADCP survey of flow velocities at the narrowest cross-section of the inlet of Menemsha Creek (Figure V-2) was executed on November 19, 2015. During this survey, velocities through the channel cross-section were measured by a boat-mounted ADCP that traversed the inlet 243 times during the course of the survey day. Flow rates were output from the model at a continuity line placed across the channel in the same location as the ADCP transect. The comparison of ADCP measurement-derived flow rates and model output is presented in Figure V-15. The comparison between model output and ADCP flow rates is very good, further indicating that the hydrodynamic model adequately represents the physics of the real system. The R^2 correlation between model output and measurements is 0.94, and the RMS error of the model output is 648 ft^3/sec, which is about 9% of the maximum measured flowrate.

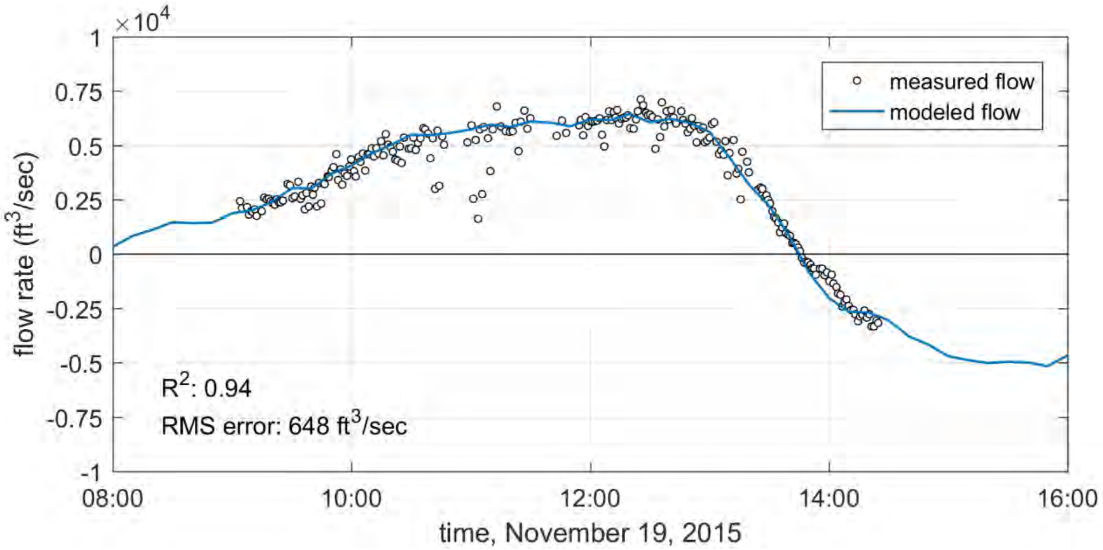

Figure V-15. Comparison of flow rates determined using ADCP velocity data and modeled flow rates at the survey transect the inlet of Menemsha Creek (Figure V-2).

V.3.4 Model Circulation Characteristics

The final calibrated model serves as a useful tool in investigating the circulation characteristics of the Menemsha-Squibnocket Pond Embayment 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. As an example, Figure V-16 shows color contours and vectors that indicate velocity during a single model time step, during a period of maximum flood currents at the inlet.

As another example, from the calibration model run of the Menemsha-Squibnocket Pond Embayment System, the total flow rate of water flowing through the system inlet at the jetties can be determined with the hydrodynamic model, similar to what was done for the ADCP corroboration of model results. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-17. During spring tides, the maximum flood flow rates reach nearly 15,000 ft^3/sec in the channel. Maximum ebb flow rates during spring tides are about two-thirds of the maximum flood flow rates, about 10,000 ft^3/sec.

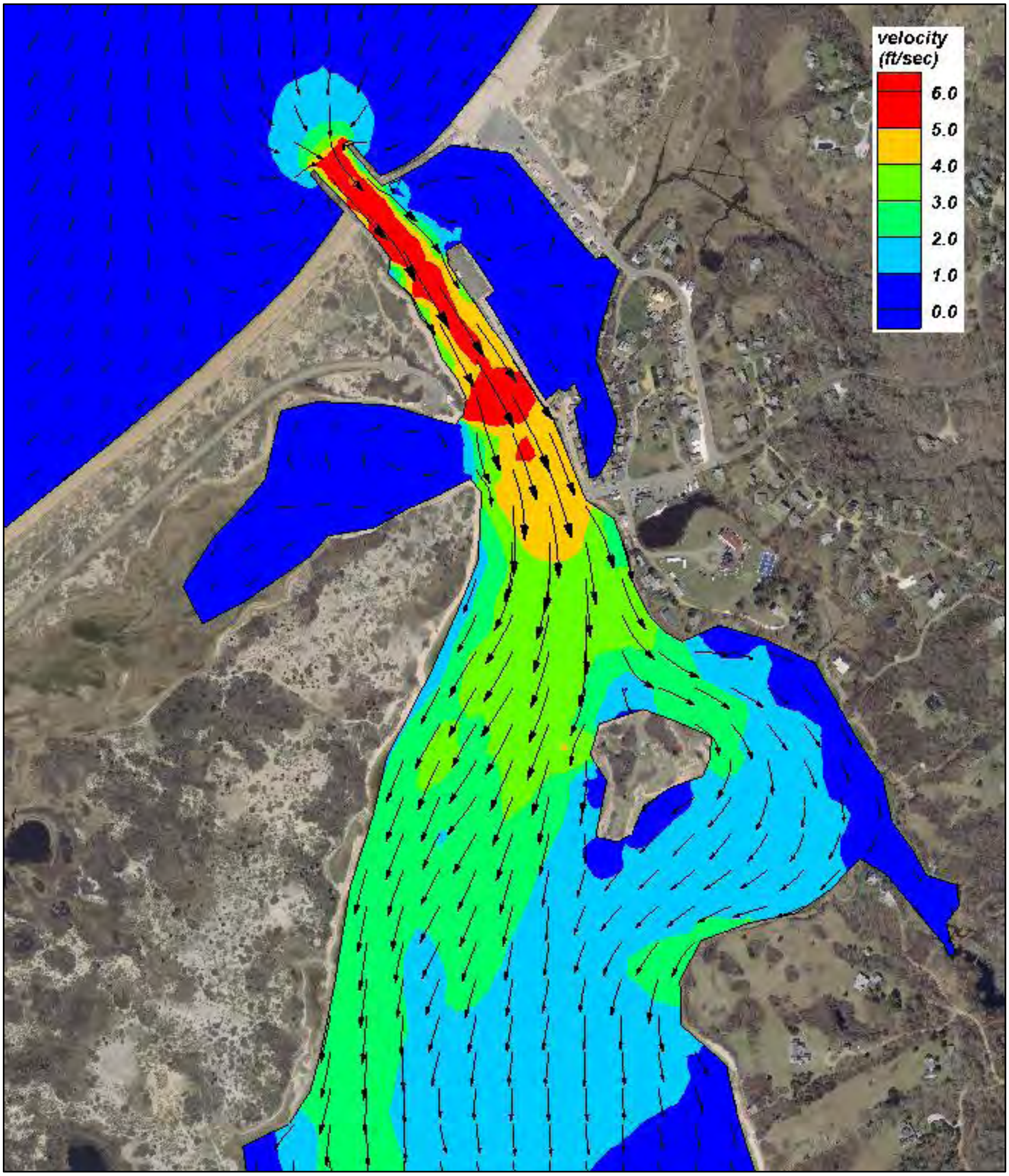

Figure V-16. Example of hydrodynamic model output for a single time step during a flooding tide at Menemsha Creek and the system inlet. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

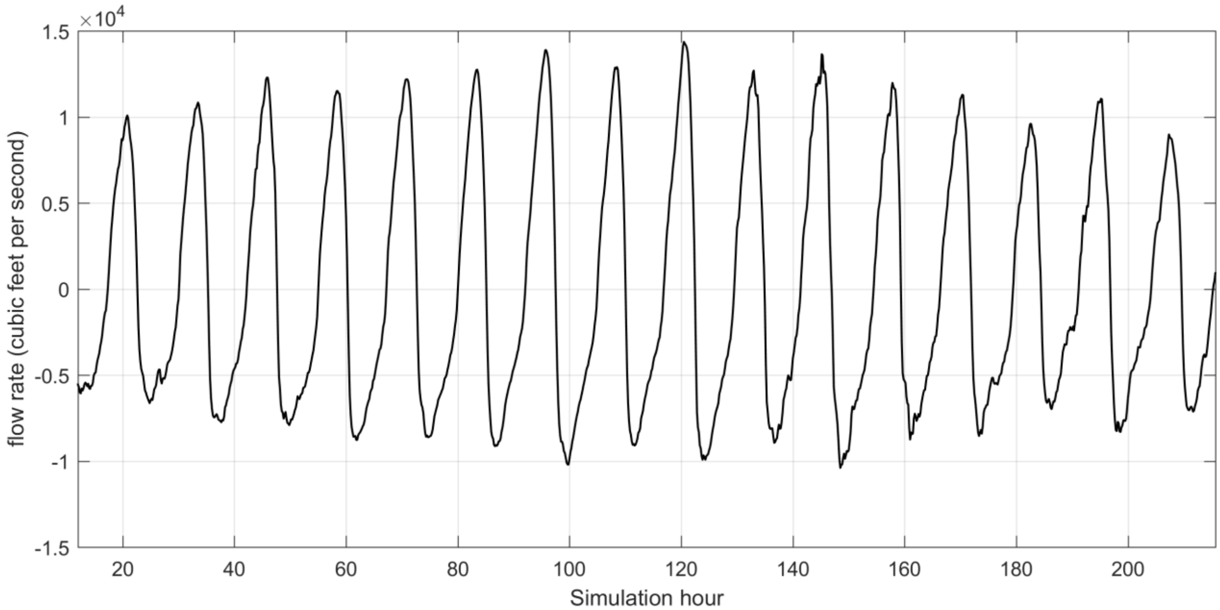

Figure V-17. Time variation of computed flow rates at the Menemsha Creek inlet. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flow indicated flooding tide flows, while negative flow indicates ebbing tide flows.

V.3.5 Flushing Characteristics

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through the inlet, the primary mechanism controlling estuarine water quality within the modeled Menemsha-Squibnocket Pond Embayment System is tidal exchange. A rising tide offshore in Vineyard Sound creates a slope in water surface from the Sound into the upper-most reaches of the estuary. 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 the system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of the harbor system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

Flushing rate, or residence time, is defined as the average time required for a parcel of water to migrate out of an estuary from points within the system. For this study, **system residence times** were computed as the average time required for a water parcel to migrate from a point within the each embayment to the entrance of the system. System residence times are computed as follows:

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

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

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

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

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

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

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. It is impossible to evaluate an estuary’s health based solely on flushing rates. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the estuary faster than the tidal circulation can flush the system. Neither are low residence times an indicator of high water quality if the water flushed into the estuary is of poor quality. Advanced understanding of water quality is obtained from the calibrated hydrodynamic model in the following section of this report (Section VI) by extending the model to include pollutant/nutrient dispersion. The water quality model provides an additional valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Menemsha Pond system.

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

Residence times were calculated as the volume of water (based on the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Model divisions used to define the system sub-embayments include 1) the entire Menemsha-Squibnocket Pond Embayment System including all attached sub-embayments, 2) Stonewall Pond, 3) Nashaquitsa Pond including Stonewall Pond and 4) Squibnocket Pond including Herring Creek. These system divisions follow the model material type areas designated in Figure V-8. Sub-embayment mean volumes and tide prisms are presented in Table V-9.

Table V-9. Embayment mean volumes and average tidal prism during simulation period for the Menemsha-Squibnocket Pond Embayment System.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Menemsha Pond (system)	561,467,989	141,977,410
Stonewall Pond	5,424,709	3,813,419
Nashaquitsa Pond (with Stonewall Pond)	37,866,939	22,218,858
Squibnocket Pond	263,881,477	899,594

Residence times were averaged for the tidal cycles comprising a representative 8 day period (17 tide cycles), and are listed in Table V-10. The modeled time period used to compute the flushing rates started October 23, 2015 , similar to the model calibration period, and included the transition from neap to spring tide conditions. The RMA-2 model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume. Since the 8 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-10. Computed System and Local residence times for embayments in the Menemsha-Squibnocket Pond Embayment System.

Embayment	System Residence Time (days)	Local Residence Time (days)
Menemsha Pond (system)	2.0	2.0
Stonewall Pond	76.2	0.7
Nashaquitsa Pond (with Stonewall Pond)	13.1	0.9
Squibnocket Pond	323.0	151.8

The computed flushing rates for the Menemsha Pond system show that as a whole, the system flushes moderately well. A flushing time of 2.0 days for the entire estuary shows that on average, water is resident in the system for less than two days. The inner reaches of the estuary have local flushing times that are less than one day.

For the sub-embayments attached to Menemsha Pond, high system residence times result due to their small volume relative to the system as a whole. The system residence time for Stonewall Pond is two orders of magnitude longer than its local residence time of only 0.7 days. This indicates that Stonewall Pond flushes efficiently, and also that water quality in this sub-embayment is strongly influenced by water quality in the downstream areas of the system.

Squibnocket Pond has the longest system and local residence times. The local residence time of 5 months indicates that this sub-embayment flushes poorly, and its water quality is strongly influenced by the poor tidal exchange with the rest of the system.

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

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

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to develop and parameterize the Menemsha and Squibnocket Ponds water quality model. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the embayments were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated hydrodynamic model representing the transport of water within the Menemsha and Squibnocket Ponds system. Files of node locations and node connectivity for the RMA-2V model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic model output used for the water quality model calibration was the 7-day (14 tide cycle) period beginning 0530 hours EDT Oct 24, 2015. This period is the same used for the flushing analysis presented in Chapter V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic “steady state”, and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

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

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates the total nitrogen concentrations in an estuary as it responds to tidal flushing and nutrient loading, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. The multi-year averages present the “best” comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. Up to 4 years of data (collected between 2000 and 2012) were available for stations in Menemsha and Squibnocket Ponds.

Table VI-1. Measured data and modeled nitrogen concentrations for the Menemsha and Squibnocket Ponds system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of all measurements. Data represented in this table were collected in the summers of 2000 through 2012.

Sub-Embayment	Monitoring station	Data Mean	s.d. all data	N	model min	model max	model average
Menemsha Creek Low	MEN 1	0.287	0.037	23	0.289	0.310	0.296
Menemsha Creek Low	MEN 2	0.341	0.078	24	0.293	0.318	0.304
Menemsha Main Basin	MEN 3	0.385	0.118	29	0.291	0.328	0.311
Menemsha Main Basin	MEN 4	0.399	0.156	25	0.385	0.423	0.404
Nashaquitsa Mouth	MEN 5	0.338	0.107	26	0.319	0.344	0.335
Nashaquitsa Basin	MEN 6	0.341	0.082	23	0.338	0.354	0.347
Menemsha Main Basin	MEN 8	0.379	0.111	23	0.360	0.374	0.368
Menemsha Main Basin	MEN 9	0.386	0.099	23	0.340	0.370	0.358
Menemsha Creek	MEN 10	0.351	0.120	22	0.290	0.326	0.308
Squibnocket Basin	SQ 1	0.763	0.321	20	0.725	0.782	0.761
Squibnocket Basin	SQ 2	0.798	0.327	22	0.788	0.798	0.793
Squibnocket Basin	SQ 3	0.769	0.386	18	0.780	0.791	0.786
Squibnocket Basin	SQ 4	0.853	0.318	15	0.812	0.822	0.817

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 Menemsha and Squibnocket Ponds 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 Menemsha and Squibnocket Ponds. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. The MEP Technical Team has utilized this model in water quality studies of other embayment systems in southeastern Massachusetts, including Pleasant Bay (Howes *et al*., 2006); New Bedford Harbor (Howes *et al*., 2008) and Edgartown Great Pond, MA (Howes *et al*., 2008).

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 watershed loading analysis of Section IV, 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 Menemsha and Squibnocket Ponds system.

Figure VI-1. Estuarine water quality monitoring station locations in the Menemsha and Squibnocket Ponds system. Station labels correspond to those provided in Table VI-1.

VI.2.1 Model Formulation

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

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

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

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

The RMA-4 model can be utilized to predict both spatial and temporal variations in total nitrogen 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 Menemsha and Squibnocket Ponds.

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 Menemsha and Squibnocket Ponds (Section V) also were used for the water quality constituent modeling portion of this study.

For each model run, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 14 day (336 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.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed and direct atmospheric deposition loads for Main Basin of Menemsha Pond, at the uppermost reaches of the pond, were evenly distributed at grid cells along the perimeter of this area. Benthic regeneration loads were distributed among all the other, non-watershed loading elements of each material type described in Chapter V.

The loadings used to model present conditions in Menemsha and Squibnocket Ponds 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 system sub-division (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. On average, in all areas of Menemsha and Squibnocket Ponds the net benthic flux is positive which indicates a net flux of nitrogen out of the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in Vineyard Sound, offshore the pond inlet, was set at 0.289 mg/L, based on SMAST monitoring data.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Menemsha			
Lower Creek	0.460	--	--
Pease Point Brook	0.844	--	--
Nashaquitsa Pond	4.074	1.668	0.972
Menemsha Creek	4.600	1.419	0.292
Menemsha Main	2.729	8.553	50.164
Squibnocket			
Black Brook	0.559	--	--
Squibnocket East	0.751	1.118	0.000
Squibnocket Main	2.027	7.890	8.220
System Total	16.044	20.649	59.648

VI.2.4 Model Calibration

Calibration of the total nitrogen model of Menemsha and Squibnocket Ponds proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (E) values were varied through the modeled system by setting different values of E for each grid material type, as designated in Section V. Observed values of E in coast estuary areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of E used in each sub-embayment of the modeled system are presented in Table VI-3. These values were used to develop the "best-fit" total nitrogen model calibration. For the case of TN modeling, "best fit" can be defined as minimizing the error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

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

For model calibration, the average modeled TN was compared to mean measured TN data values, at both water-quality monitoring stations. The calibration target would fall near the modeled mean because the monitoring data are collected, as a rule, during mid ebb tide.

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for the Menemsha and Squibnocket Ponds system. Model divisions correspond to those shown in Figure V-8.

Embayment Division	E m^2/sec
Offshore	3.0
Inlet channel	1.0
Menemsha Creek	2.0
Menemsha Main - shallow	2.0
Nashaquitsa Pond	3.0
Stone Wall Pond	3.0
Squibnocket Herring Run	0.8
Squibnocket - Main Basin	1.8
Squibnocket - East Basin	1.0
Black Brook	1.0
State Road Bridge	4.0
Menemsha Main - deep	2.0

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for each system. The computed R^2 correlation is 0.98 and the root mean squared (rms) error is 0.03 mg/L, which demonstrate an excellent fit between modeled and measured data for this system.

A contour plot of calibrated model output is shown in Figure VI-4. In this figure, color contours indicate nitrogen concentrations throughout the model domain. The output in these figures show average total nitrogen concentrations, computed using the full 14-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 Menemsha and Squibnocket Ponds system using salinity data collected at the same stations as the nitrogen data. For the salinity verification, none of the model dispersion coefficients were changed from the values used in the TN calibration. Comparisons of modeled and measured salinities are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. The RMS error of the model is 1.1 ppt.

The only required inputs into the RMA4 salinity model of the system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, rain, surface water and groundwater inputs. The open boundary salinity was set at 31.2 ppt. All groundwater input salinities were set at 0 ppt. Groundwater flows to the pond included in the model were 0.23 ft^3/sec (555 m^3/day) for Lower Creek, 1.77 ft^3/sec (4,341 m^3/day) for Nashaquitsa Pond, 1.42 ft^3/sec (3,477 m^3/day) for Menemsha Creek and 2.24 ft^3/sec (5,482 m^3/day) for main basin of Menemsha Pond. Pease Point Brook was represented as a freshwater stream flow at 0.565 ft^3/sec (1,382 m^3/day). For Squibnocket Pond groundwater flows to the pond included 0.58 ft^3/sec (1,416 m^3/day) for Black Brook, 0.631 ft^3/sec (1,545 m^3/day) for Squibnocket Pond East, and 2.40 ft^3/sec (5,879 m^3/day) for Squibnocket Pond. Groundwater flows were distributed evenly in the model along elements positioned along the model's land boundary.

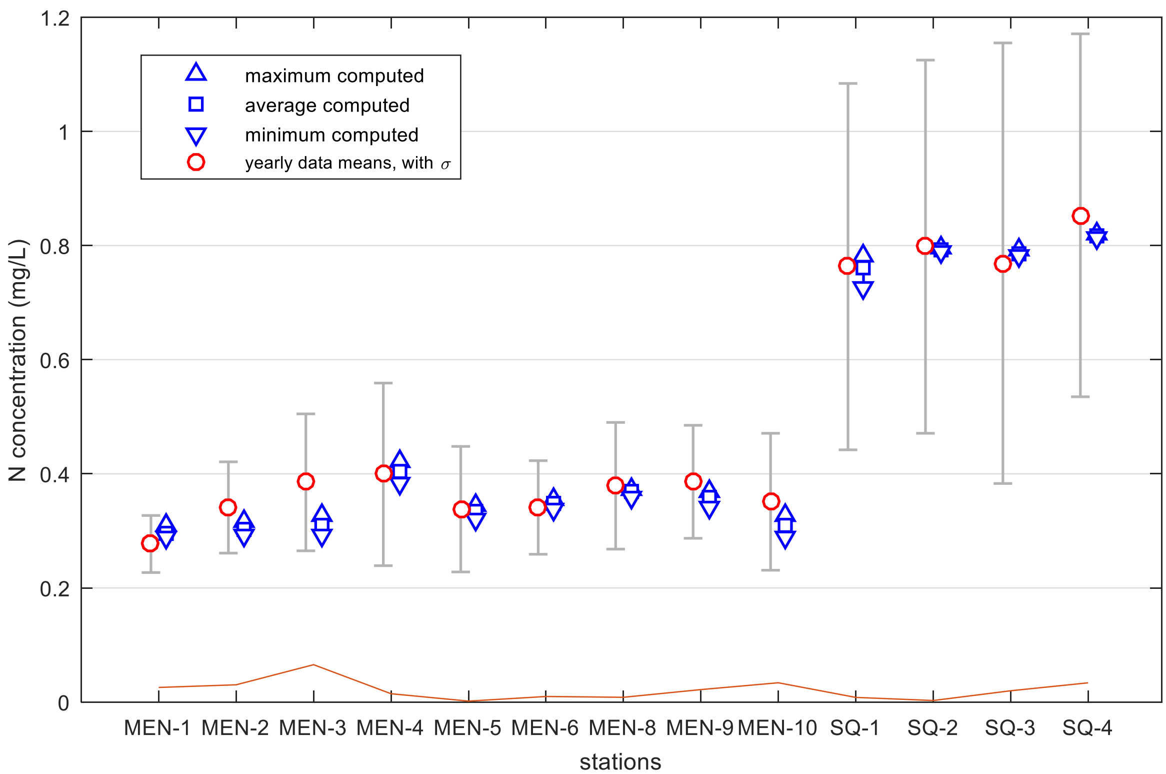

Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Menemsha and Squibnocket Ponds system. Station labels correspond with the MEP IDs provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed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

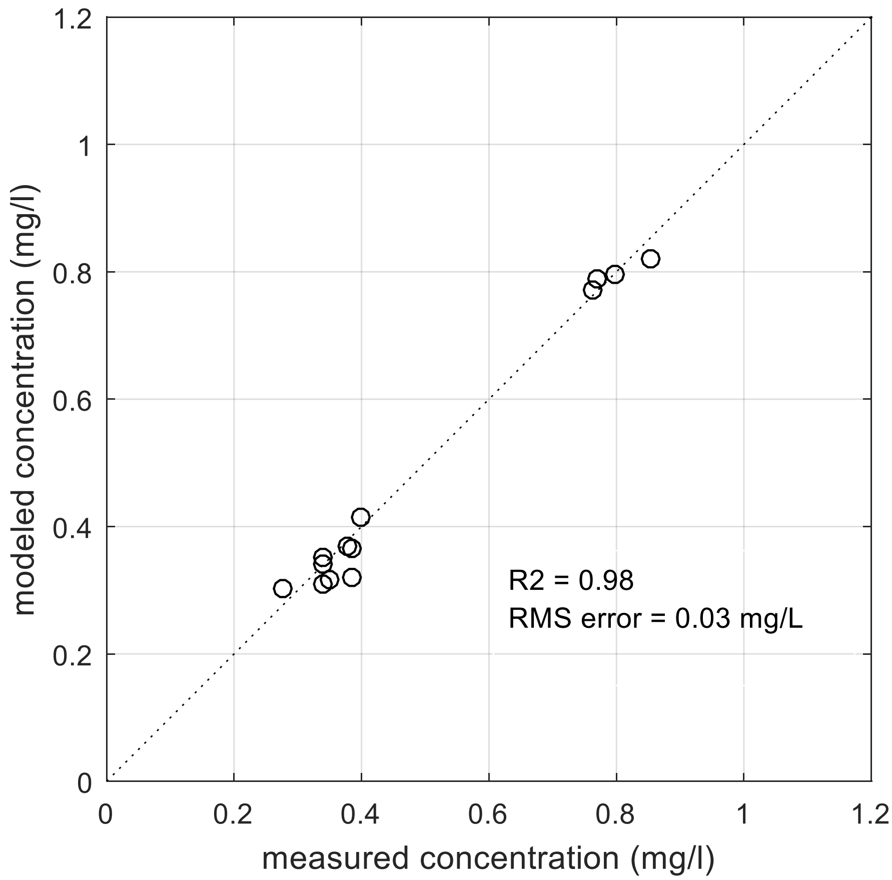

Figure VI-3. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are 0.98 and 0.027 mg/L respectively. The 0.98 R^2 value for the Menemsha Squibnocket model is indicative of a good fit between measured data and model output. The R^2 coefficient determined for the Menemsha Squibnocket model is influenced by the number of WQ stations in the pond and relatively small gradient in TN concentrations between the inlet and upper inland reaches. Higher R^2 values are generally easier to achieve in systems with a larger spread in TN concentrations. The model calibration is always determined as the best fit between all the various WQ model inputs and the measured WQ data.

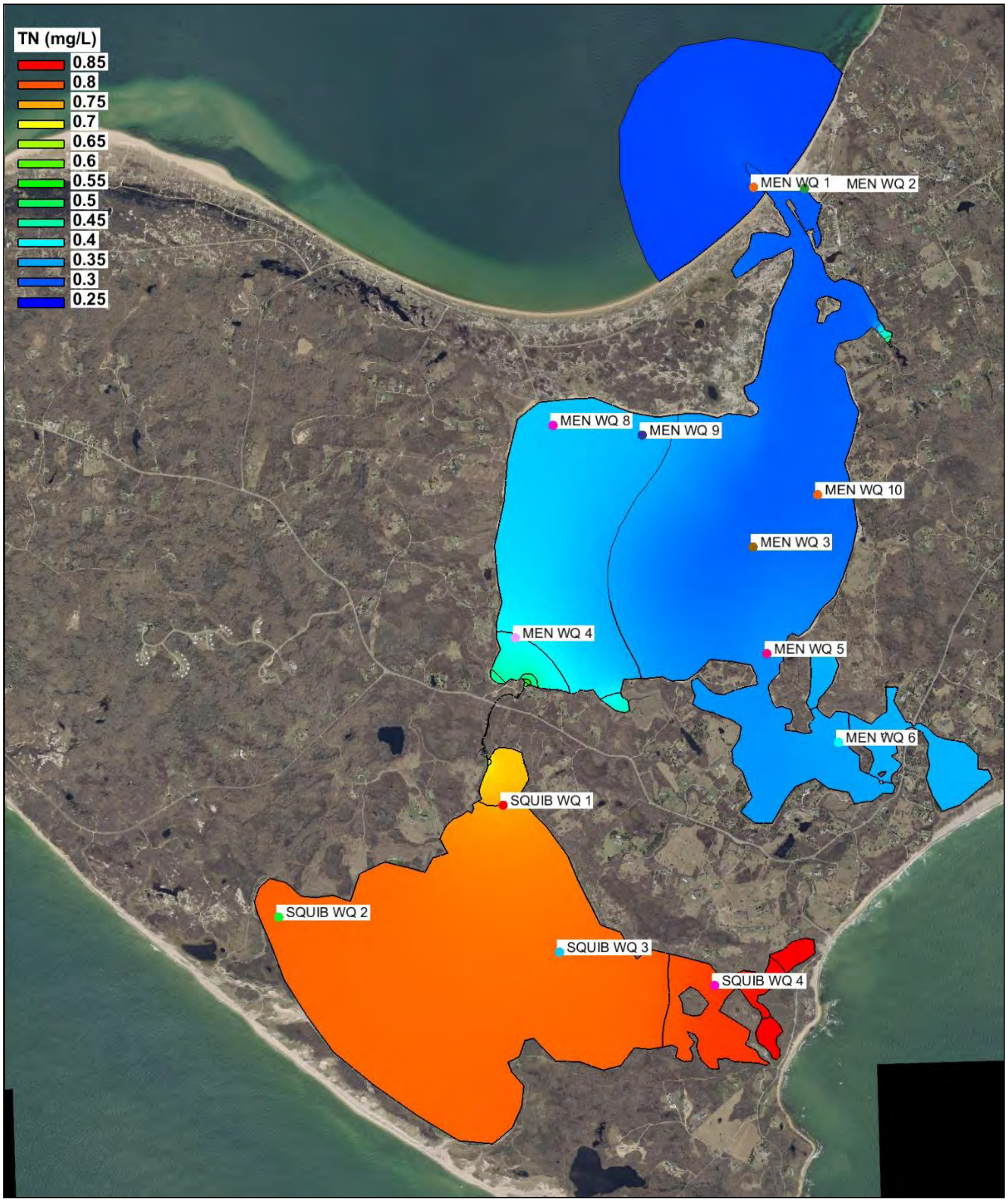

Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Menemsha and Squibnocket Ponds system.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

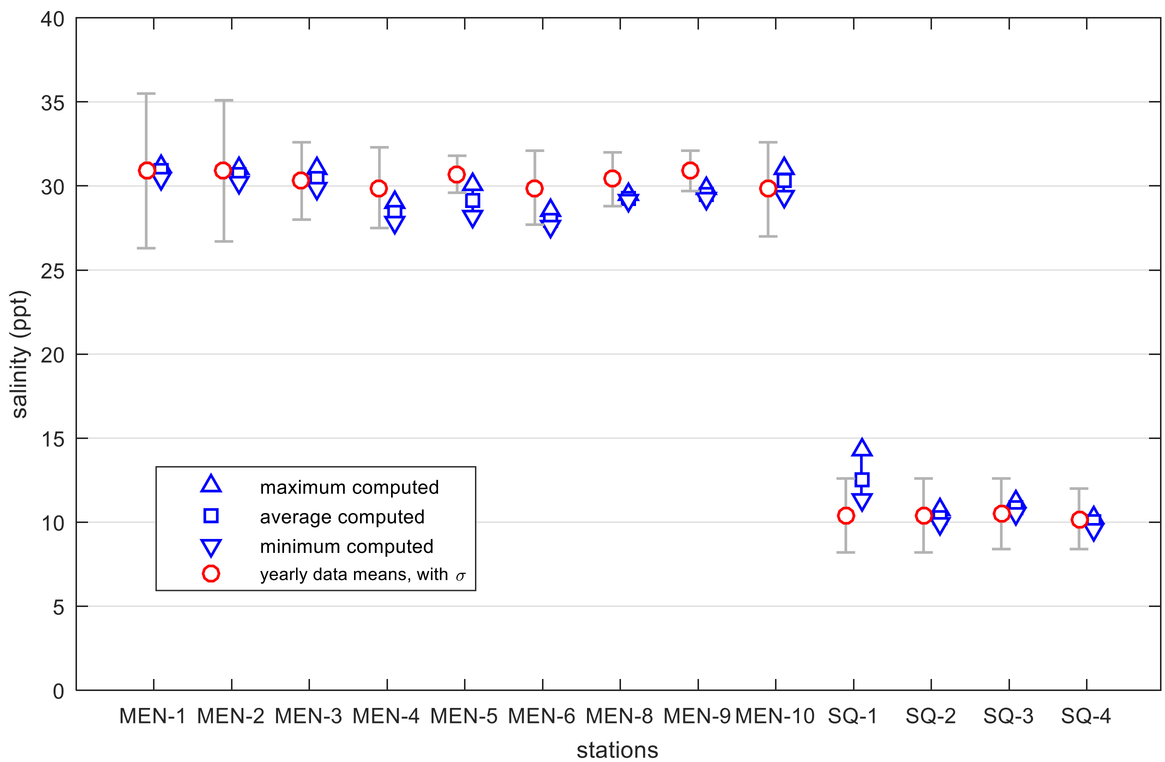

Figure VI-5. Comparison of measured and calibrated model output at stations in Menemsha and Squibnocket Ponds. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers),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

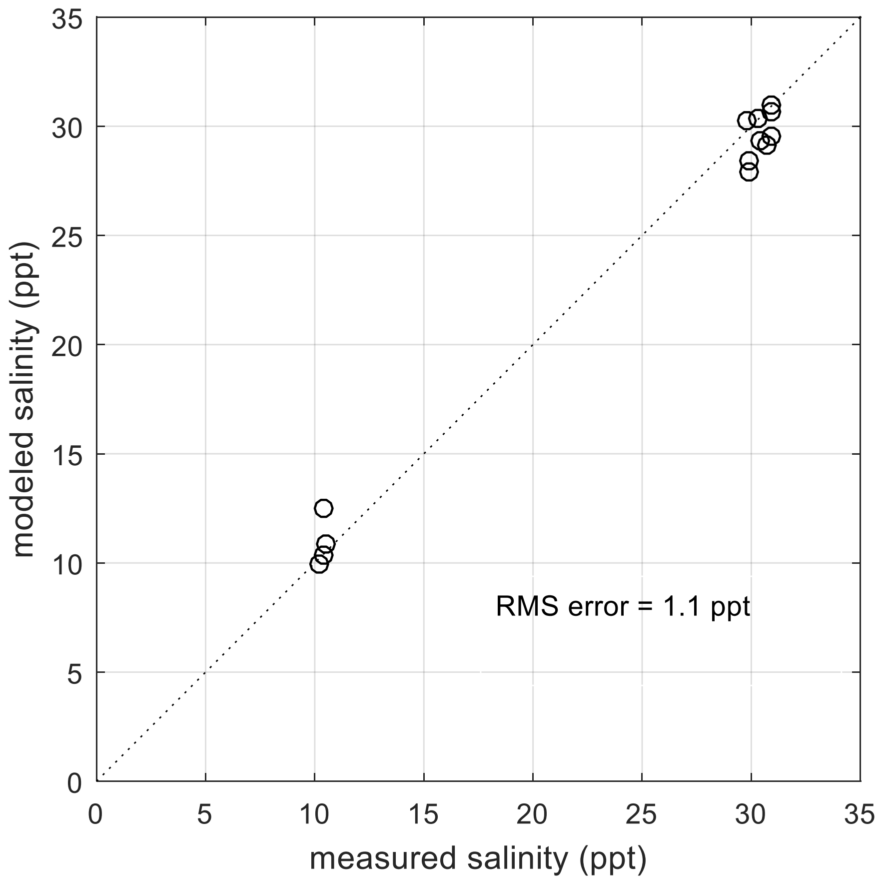

Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. RMS error for this model verification run is 1.1 ppt.

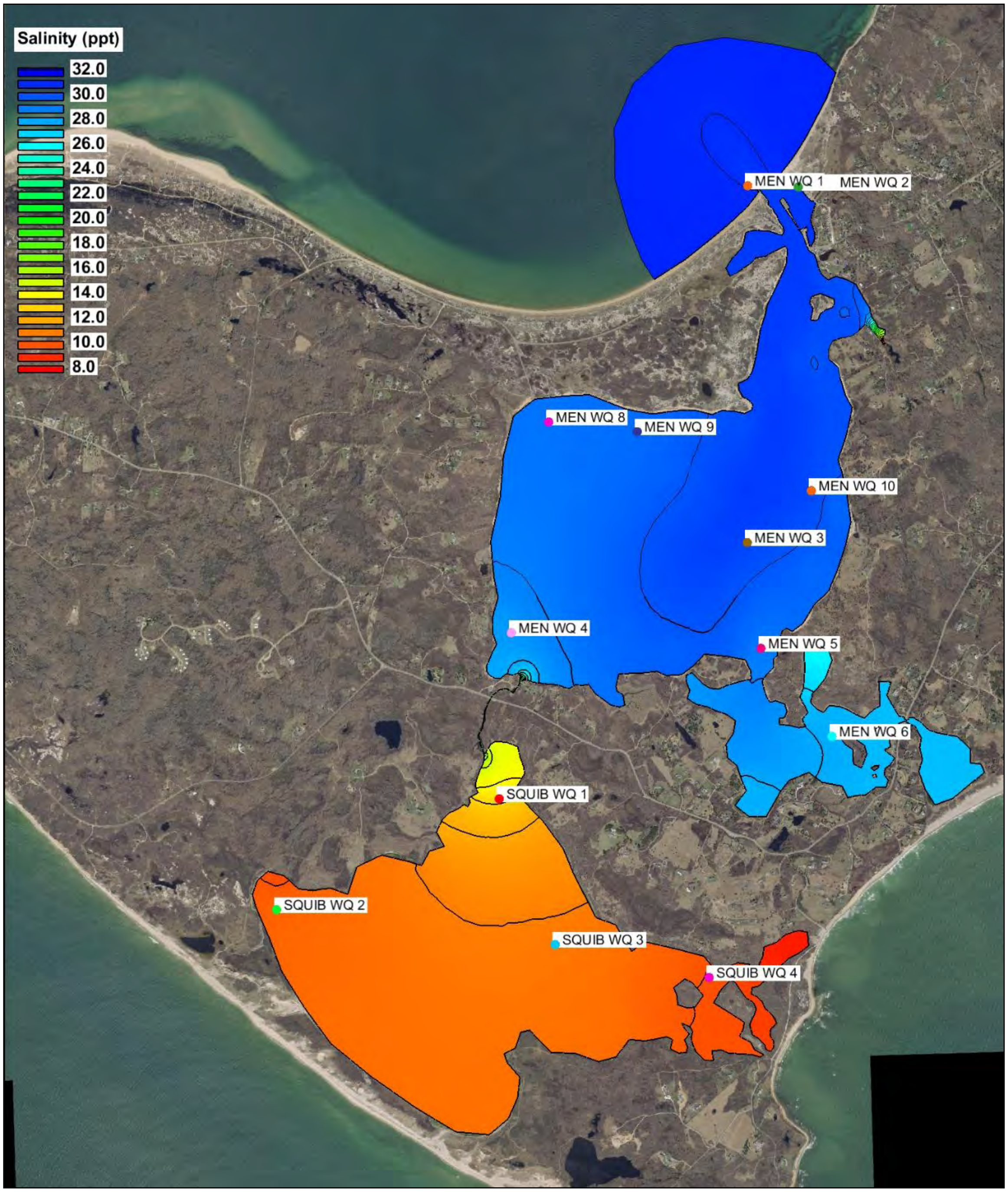

Figure VI-7. Contour Plot of average modeled salinity (ppt) in the Menemsha and Squibnocket Ponds system.

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic (“no-load”) loading scenarios of the Menemsha and Squibnocket Ponds 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
Menemsha					
Lower Creek	0.46	0.52	+12.5%	0.06	-86.9%
Pease Point Brook	0.84	1.22	+44.2%	0.19	-76.9%
Nashaquitsa Pond	4.07	5.42	+33.0%	0.74	-81.9%
Menemsha Creek	4.60	5.11	+11.1%	0.65	-85.9%
Menemsha Main	2.73	4.86	+78.1%	0.77	-71.7%
Squibnocket					
Black Brook	0.56	0.95	+70.1%	0.19	-66.7%
Squibnocket East	0.75	0.98	+30.7%	0.20	-73.0%
Squibnocket Main	2.03	4.84	+138.6%	0.67	-66.9%
System Total	16.04	23.89	+48.9%	3.47	-78.4%

VI.2.6.1 Build-Out

A breakdown of the total nitrogen load entering each sub-embayment is shown in Table VI-5 for the modeled build-out scenario. 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:

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Following development of the nitrogen loading estimates for the build-out scenario, the water quality models of the system was run to determine nitrogen concentrations at each monitoring station (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Vineyard Sound) remained identical to the existing conditions modeling scenarios. For build-out, the increase in modeled TN concentrations is greatest at the monitoring station MEN 10, at the boundary between the main basin and Menemsha Creek, where concentrations increased by 9%. A contour plot showing average TN concentrations throughout the Menemsha and Squibnocket Ponds system is presented in Figure VI-8 for the modeling of build-out loads.

Table VI-5. **Build-out** scenario sub-embayment and surface water loads used for total nitrogen modeling of the Menemsha and Squibnocket Ponds 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)
Menemsha			
Lower Creek	0.518	0.000	0.000
Pease Point Brook	1.216	0.000	0.000
Nashaquitsa Pond	5.419	1.668	1.026
Menemsha Creek	5.110	1.419	0.292
Menemsha Main	4.860	8.553	52.515
Squibnocket			
Black Brook	0.951	0.000	0.000
Squibnocket East	0.981	1.118	0.000
Squibnocket Main	4.838	7.890	9.714
System Total	23.893	20.649	63.548

Table VI-6. Comparison of model average total N concentrations from present loading and the **build-out scenario**, with percent change over background in Vineyard Sound (0.287 mg/L), for the Menemsha Squibnocket system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out (mg/L)	% change
Menemsha Creek Low	MEN 1	0.296	0.296	+6.9%
Menemsha Creek Low	MEN 2	0.304	0.305	+7.8%
Menemsha Main Basin	MEN 3	0.311	0.313	+7.5%
Menemsha Main Basin	MEN 4	0.404	0.412	+6.1%
Nashaquitsa Mouth	MEN 5	0.335	0.339	+8.1%
Nashaquitsa Basin	MEN 6	0.347	0.353	+9.5%
Menemsha Main Basin	MEN 8	0.368	0.373	+6.4%
Menemsha Main Basin	MEN 9	0.358	0.363	+6.5%
Menemsha Creek	MEN 10	0.308	0.310	+9.0%
Squibnocket Basin	SQ 1	0.761	0.783	+4.6%
Squibnocket Basin	SQ 2	0.793	0.815	+4.2%
Squibnocket Basin	SQ 3	0.786	0.807	+4.2%
Squibnocket Basin	SQ 4	0.817	0.839	+4.2%

VI.2.6.2 No Anthropogenic Load

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

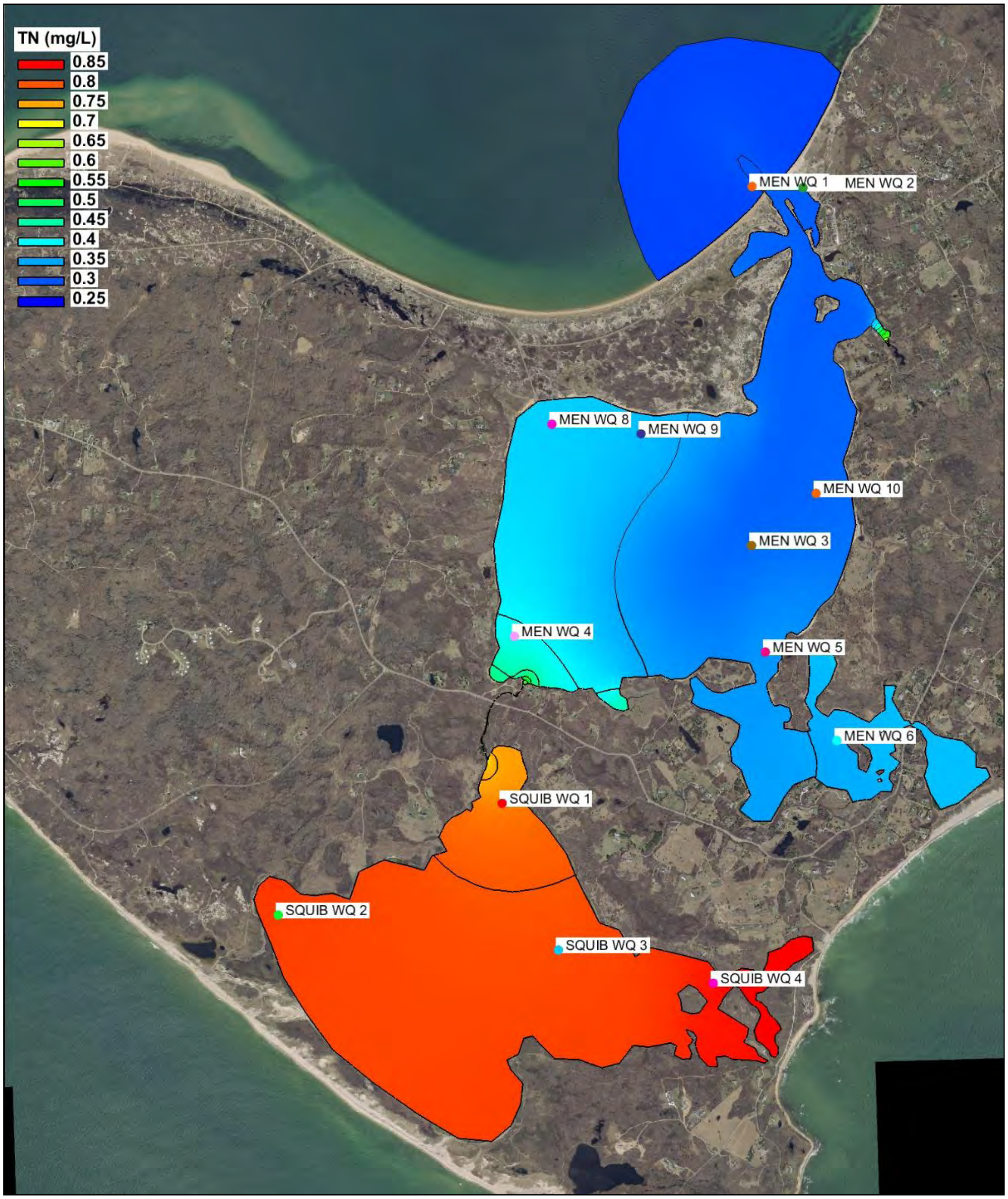

Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Menemsha and Squibnocket Ponds system, for projected build-out scenario loading conditions.

Table VI-7. “**No anthropogenic loading**” (“no load”) sub-embayment and surface water loads used for total nitrogen modeling of the Menemsha Squibnocket 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)
Menemsha			
Lower Creek	0.060	0.000	0.000
Pease Point Brook	0.195	0.000	0.000
Nashaquitsa Pond	0.737	1.668	0.864
Menemsha Creek	0.647	1.419	0.292
Menemsha Main	0.773	8.553	-1.161
Squibnocket			
Black Brook	0.186	0.000	0.000
Squibnocket East	0.203	1.118	0.000
Squibnocket Main	0.671	7.890	6.974
System Total	3.471	20.649	6.970

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations at each monitoring station. Similar to the procedure followed for the build-out simulation, total nitrogen concentrations in the receiving waters (i.e., Vineyard Sound) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from “no load” was small, with all areas of the system experiencing reductions less than 25%, compared to the background concentration of 0.287 in Vineyard Sound (Table VI-8). A contour plot showing TN concentrations throughout the system is shown pictorially in Figure VI-9.

Table VI-8. Comparison of model average total N concentrations from present loading and the “**No anthropogenic loading**” (“no load”), with percent change over background in Vineyard Sound (0.287 mg/L), for the Menemsha Squibnocket system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	no-load (mg/L)	% change
Menemsha Creek Low	MEN 1	0.296	0.294	-14.9%
Menemsha Creek Low	MEN 2	0.304	0.300	-20.4%
Menemsha Main Basin	MEN 3	0.311	0.307	-16.3%
Menemsha Main Basin	MEN 4	0.404	0.393	-10.0%
Nashaquitsa Mouth	MEN 5	0.335	0.326	-19.2%
Nashaquitsa Basin	MEN 6	0.347	0.332	-25.5%
Menemsha Main Basin	MEN 8	0.368	0.359	-10.9%
Menemsha Main Basin	MEN 9	0.358	0.350	-11.4%
Menemsha Creek	MEN 10	0.308	0.304	-18.5%
Squibnocket Basin	SQ 1	0.761	0.743	-3.8%
Squibnocket Basin	SQ 2	0.793	0.776	-3.4%
Squibnocket Basin	SQ 3	0.786	0.769	-3.4%
Squibnocket Basin	SQ 4	0.817	0.794	-4.4%

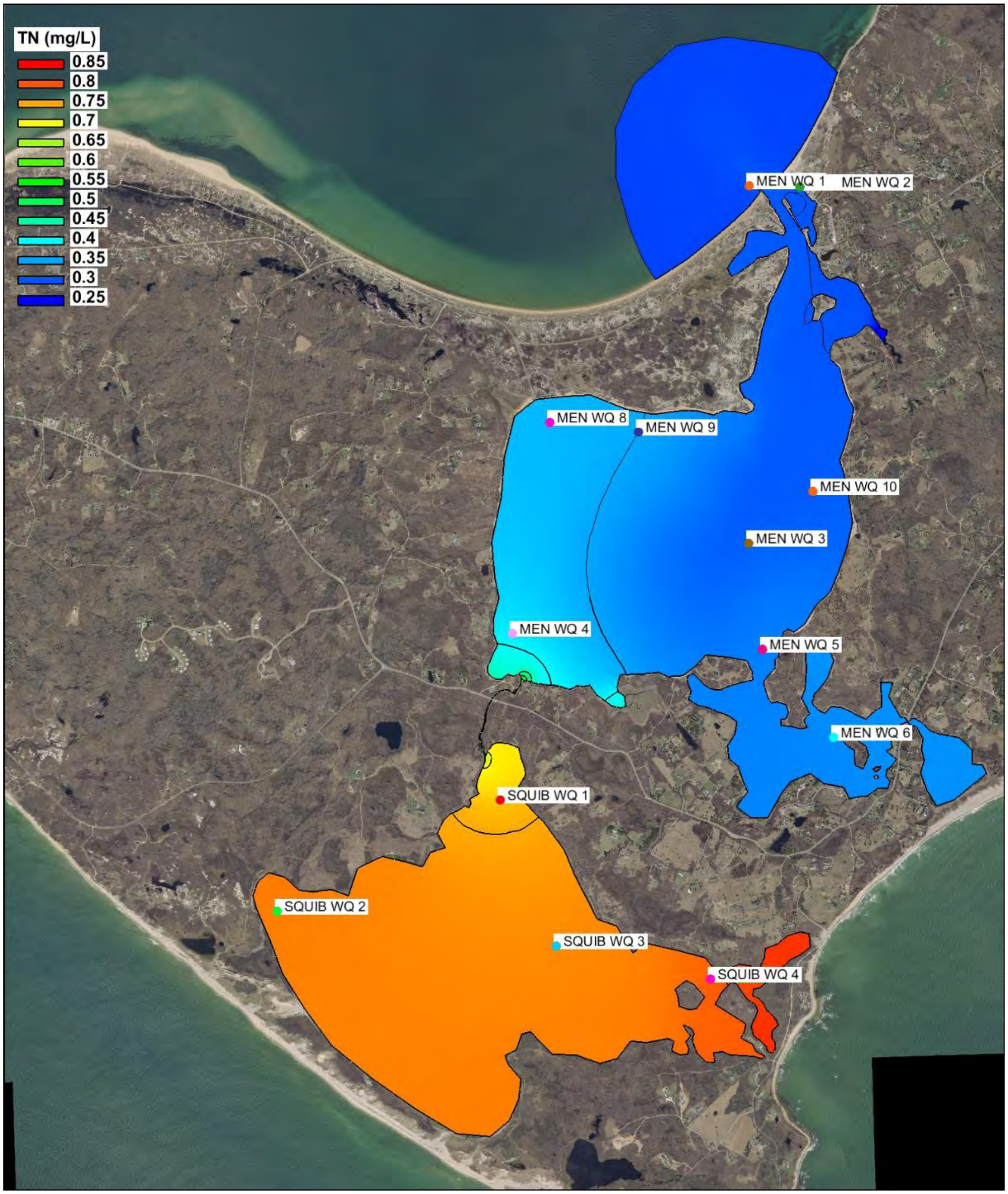

Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in Menemsha and Squibnocket Ponds, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Menemsha-Squibnocket Pond Embayment System (inclusive of Nashaquitsa Pond and Stonewall Pond) in the Town of Chilmark and Aquinnah, MA, the MEP assessment is based upon data from the water quality monitoring program developed by the Towns, the Martha's Vineyard Commission and the Wampanoag Tribe of Aquinnah. Technical assistance was provided by the Coastal Systems Program from SMAST, as was field survey and historical data collected under the programmatic umbrella of the Massachusetts Estuaries Project. These data include temporal surveys of eelgrass distribution; surveys of benthic animal communities and sediment characteristics; and time-series measurements of dissolved oxygen and total pigment (chlorophyll-*a* + pheophytin) during the summer and fall of 2007. Figures VII-1a,b show the dissolved oxygen mooring locations. These data form the basis of an assessment of the present health of the system, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for this system (Section VIII). Part of the MEP assessment necessarily includes confirmation that the critical nutrient for management in any embayment is nitrogen and determination that a system is or is not impaired by nitrogen enrichment. Analysis of inorganic N/P molar ratios within the water column of the Menemsha-Squibnocket Pond Embayment System support the contention that nitrogen is the nutrient to be managed to control negative effects of nutrient over-enrichment. The estuarine reaches within the Menemsha-Squibnocket Pond Embayment System follow the general pattern, where the Redfield Ratio (inorganic N/P) is significantly less than 16 as seen in from the long term water quality monitoring program (3.1-5.7 in Menemsha Pond,1.4-2.7 in Squibnocket Pond). Redfield ratios >16 generally indicate phosphorus and <16 indicate nitrogen additions will cause eutrophication, respectively. This is also supported by the low levels of total dissolved inorganic nitrogen (2-3 uM) during summer months. These data indicate that nitrogen additions will increase phytoplankton production, organic matter levels and turbidity within this system. This was also the conclusion of the Martha's Vineyard Commission assessment of 2001 (MVC 2001 updated 2010).

Increased phytoplankton and organic matter levels increase oxygen consumption within the waters and sediments and increase the extent of oxygen depletion and habitat impairment. It should be noted that nitrogen enrichment occurs through two primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with low nitrogen offshore waters. Menemsha Pond has seen increasing nitrogen loading from its watershed from shifting land-uses and due to changes in hydrodynamic characteristics as channels fill in with sediments and require periodic dredging. Squibnocket Pond is particularly sensitive to increased nitrogen inputs from its watershed due to its highly restricted tidal exchange. Its watershed has relatively low development, but its large water sheet increases the impact of direct atmospheric deposition of nitrogen. Squibnocket Pond's water quality appears to be primarily controlled by its restricted tidal exchange with only secondary control by watershed inputs. Fundamentally, restrictions of tidal exchange increase the sensitivity of all temperate estuaries to nitrogen inputs.

Figure VII-1a. Aerial Photograph of Menemsha Pond and its tributary basins of Nashaquitsa and Stonewall Ponds in the Towns of Chilmark and Aquinnah showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2007 and 2012 (Menemsha West Basin re-deployment due to instrument failure in 2007).

Figure VII-1b. Aerial Photograph of the Squibnocket Pond portion of the Menemsha-Squibnocket Pond Embayment System in the Towns of Chilmark and Aquinnah showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2007 and 2012 (Squib-West re-deployment due to instrument failure in 2007).

The Menemsha-Squibnocket Pond Embayment System is continually being restructured by coastal processes related to inlet dynamics but also fundamental changes in embayment structure due to storm related wash-over events, particularly the Squibnocket Pond. Wash-over of the barrier beach/dune system during major storms has been periodically introducing marine water into Squibnocket Pond thereby affecting the salinity regime of the pond the associated ecology. The MEP assessment and threshold analysis takes into account the complex interactions between the two main basins (Menemsha Pond and Squibnocket Pond) of the embayment system.

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 stable. The concept is to use species that persist for a long time and which integrate environmental conditions over seasonal to annual intervals, such as eelgrass or benthic animal communities. 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 total pigment (mainly chlorophyll-*a* and a proxy for phytoplankton biomass; Section VII.2), (2) eelgrass distribution and coverage over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Other observations relating to sediment type and accumulations of macroalgae are also considered.

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 the basins of Squibnocket Pond and Menemsha Pond at critical locations. The sensors were situated such that they would be representative of dissolved oxygen conditions within each major sub-basin comprising the overall embayment system, namely Menemsha Creek, Menemsha Pond, Nashaquitsa Pond, Stonewall Pond and Squibnocket Pond. The five 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 habitat quality and nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal embayments, providing both spawning areas, habitat structure and sediment stabilization. Mapping of the eelgrass beds within the overall Menemsha-Squibnocket Pond Embayment System was completed by the MassDEP Eelgrass Mapping Program (C. Costello) however, no quantitative information on eelgrass distribution was found by the MEP for Squibnocket Pond and no surveying or evaluation of aerial photography was completed by the MassDEP Eelgrass Mapping Program for that portion of the system. This is most likely due to poor aerial imagery for the 1951 time point and access issues. It should be noted, however, that in diver surveys by MEP staff of Squibnocket Pond in 2007, no eelgrass was observed. Temporal trends in the distribution of eelgrass beds are typically used by the MEP to assess the stability of the habitat and to determine trends potentially related to increasing or decreasing nutrient enrichment due to changes in watershed inputs or tidal flushing. 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 relatively low levels of nitrogen and limited phytoplankton production (blooms) within the main basin of Menemsha Pond, conditions generally supportive of healthy eelgrass habitat. Nitrogen enrichment and its effects are clearly seen in the sub-basins of Nashaquitsa Pond and Stonewall Pond in their water quality and the significant decline of eelgrass coverage. Further nitrogen additions as watershed build-out continues will result in more impairment to habitats in these tributary basins and decline in eelgrass in the deeper areas of Menemsha Pond. As nitrogen is the nutrient controlling water quality, it needs to be the focus of management actions, either nitrogen source reductions or increases in tidal flushing.

While a temporal change in eelgrass distribution typically provides a basis for evaluating increases (nitrogen loading) or decreases (increased flushing from dredging channels) in nitrogen enrichment within an embayment system, only portions of the overall system have historically supported eelgrass (Menemsha, Nashaquitsa, Stonewall Ponds). In the case of no persistent eelgrass habitat (such as in Squibnocket Pond), benthic animal indicators were used to assess the level of habitat health from "healthy" (low organic matter loading, high D.O.) to "highly stressed" (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of their habitat. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life-history information on the species and a wide variety of field studies within southeastern Massachusetts waters, including the Wild Harbor oil spill, benthic population studies in Buzzards Bay (Sanders, H.L. 1960, Sanders, H.L. *et.al.*, 1980, Tian, Y.Q., J.J. Wang, J. A. Duff, B.L. Howes and A. Evgenidou. 2009) and New Bedford (Howes, B.L. and C.T. Taylor, 1990), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H') and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 4 mg L^{-1}, 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 tidally influenced waters of the Menemsha-Squibnocket Pond Embayment 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-2). 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 Menemsha-Squibnocket Pond Embayment System (Figure VII-1a,b). 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 August through mid-September. The majority of the mooring data from the Menemsha-Squibnocket Pond system were collected during the summer of 2007 with two redeployments in 2012 due to instrument failure (Menemsha-West {also referred to as Menemsha-inner} and Squibnocket-West).

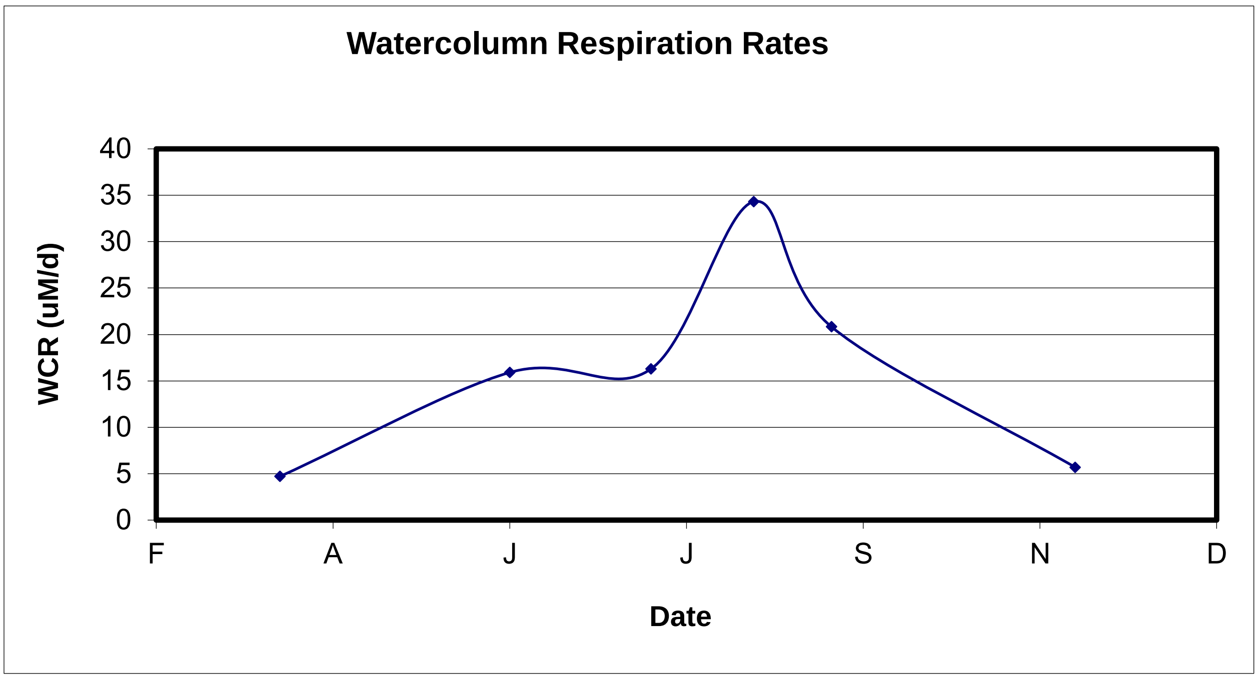

Figure VII-2. Average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Menemsha-Squibnocket Pond Embayment System evaluated in this assessment showed high frequency variation in water column oxygen and chlorophyll levels, related to diurnal influences. These variations were more pronounced at specific mooring locations such as was observed in Stonewall Pond, which had the highest phytoplankton biomass. 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 specific mooring sites, underscores the need for continuous monitoring within these systems.

Dissolved oxygen and chlorophyll-*a* records were evaluated both for temporal trends and to determine the percent of the 61 to 83 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

The level of oxygen depletion and the magnitude of daily oxygen excursion and total pigment levels as a measure of phytoplankton biomass indicate low to moderate nutrient enriched waters throughout large portions of the Menemsha Pond component basin and more moderate to high nutrient enriched water in Squibnocket Pond (Figures VII-3 through VII-18). It should be noted that there was limited data available on chlorophyll and bottom water oxygen from monitoring efforts, however the general patterns paralleled the more detailed information from the 2007 and 2013 time-series monitoring. Overall, the oxygen data is consistent with a high level of organic matter enrichment, particularly in Squibnocket Pond, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-*a*. The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels at specific locations in the embayment system are consistent with the nitrogen levels within the various basins (Section VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of each of the component sub-embayment basins.

The oxygen records show that the innermost sub-embayment of Menemsha Pond, specifically the Stonewall Pond tributary of Nashaquitsa Pond, which collectively receives significant watershed nitrogen loading relative to tidal flushing rates and has the largest daily oxygen excursions (a nutrient related response) among the four moorings deployed in the Menemsha Pond sub-system. Similarly, the innermost mooring locations (Squibnocket-south, east, west) in the Squibnocket Pond basin also showed large oxygen excursions, a response to the organic rich characteristics of the basin sediments and poor circulation and exchange with Menemsha Pond. Only the northern mooring showed relatively low oxygen excursion and depletion, with relatively low chlorophyll a levels, likely associated with its proximity to the tidal channel (herring run) which carries the tidal exchange between Squibnocket Pond and the relatively low nitrogen waters of Menemsha Pond main basin. It should be noted that 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 greater oxygen depletion at night (photosynthesis stops); than during daytime, particularly in waters with increased phytoplankton (or epibenthic algae) production. In these waters oxygen levels will rise in daylight to above atmospheric equilibration levels which in shallow systems, such as at the mooring locations, is generally ~7-8 mg L^{-1}.

Measured dissolved oxygen depletion indicates that portions of the Menemsha-Squibnocket Pond Embayment System, specifically Stonewall Pond and Squibnocket Pond, show oxygen stress. The largest oxygen depletions and excursions were observed in Squibnocket Pond, particularly in the more poorly flushed areas farther from the herring run. The oxygen record obtained from the western sector of Squibnocket Pond showed significant oxygen depletion particularly in the beginning of the deployment period, with oxygen stress decreasing over the course of the deployment. The main basin of Menemsha Pond did not show signs of oxygen stress, however, the tributary basin farthest from the tidal inlet, Stonewall Pond, showed large oxygen depletions similar to what was observed at the Squibnocket Pond-south, east mooring locations. It appears that the sites that are furthest away from an inlet with reduced access to low nitrogen waters also have the greatest oxygen stress. These areas are also depositional environments with sediments that are high in organic content. The observed spatial pattern indicated that the level of oxygen depletion (Table VII-1a,b) and chlorophyll-*a* (Table VII-2a,b) and total nitrogen levels increased with increasing distance from the tidal inlet to Menemsha Pond as well as increasing distance from the culvert connecting Menemsha Pond to Squibnocket Pond. Squibnocket Pond with its highly restricted tidal exchange also supports much higher nitrogen levels than the rest of this embayment system. Given its structure, the conditions in Squibnocket Pond appear to be mainly related to its very low flushing which appears to explain the historic lack of eelgrass coverage in this basin. Improving the exchange between Stonewall Pond and Nashaquitsa Pond to Menemsha Pond as well as the exchange between Squibnocket Pond and Menemsha Pond (or periodic breach of Squibnocket Pond through the barrier beach to directly exchange pond waters with low nitrogen offshore waters likely provides the only mechanism to sufficiently lower nitrogen levels (and associated negative effects) to improve benthic animal habitat throughout this basin.

The pattern of oxygen depletion, elevated chlorophyll-*a* and nitrogen levels are consistent with the present quality of eelgrass (Section VII.3) and benthic animal habitats (Section VII.4) observed throughout the Menemsha-Squibnocket Pond Embayment System. These assessments indicate an estuarine system that is beyond its ability to assimilate nitrogen loads without impairment.

The embayment specific oxygen and chlorophyll-*a* results are as follows:

Menemsha Inlet – (Figures VII-3 and VII-4):

The Menemsha Creek mooring location represents the channel connecting Vineyard Sound to the main basin of Menemsha Pond. The mooring was deployed on a pier adjacent to the channel to characterize oxygen conditions in this segment of the system (Figure VII-1a). Daily excursions (maximum to minimum) in oxygen levels at this location were moderate, generally varying approximately 2 mg L^{-1}. Oxygen levels varied primarily with tide and light (diurnal cycle) as the pond exchanged water through the inlet with every tidal cycle. Lowest oxygen was generally observed in the early morning on ebbing tides. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Maximum oxygen levels did not exceed air equilibration (% air saturation), which occurs when nutrient enrichment has stimulated phytoplankton growth and oxygen production (photosynthesis), and the moderately ranging oxygen conditions are consistent with the generally low to moderate chlorophyll-a conditions at this location during the deployment period. Both the moderate oxygen levels (4 to 8 mg L^{-1}), the moderate daily excursion and the moderate chlorophyll levels (5-10 ug L^{-1}) suggests that significant organic matter enriched conditions are not extant in this region of the basin during the measurement period.

Oxygen levels were generally above 6 mg L^{-1} (77% of record) over the 62 day record (Figure VII-3). Oxygen levels at this site were rarely <5 mg L^{-1} (4% of record) and did not drop below 4 mg L^{-1}, the critical threshold for oxygen stress in estuaries (Table VII-1a). The infrequent oxygen declines were generally consistent with the moderate to low levels of phytoplankton biomass as measured by chlorophyll-*a* for the complete deployment period. Chlorophyll-*a* averaged 7.3 ug L^{-1} over the record and exceeded only periodically exceeded 10 ug L^{-1} (10% of record). The chlorophyll-*a* levels were generally constant throughout the mooring deployment (5-10 ug L^{-1}), however, they were slightly higher in the first half of the deployment. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality in temperate embayments, higher than the ~7 ug L^{-1} observed in Menemsha Creek. These levels of chlorophyll-*a* are indicative of good quality water entering the main basin of Menemsha Pond (Table VII-2a, Figure VII-4).

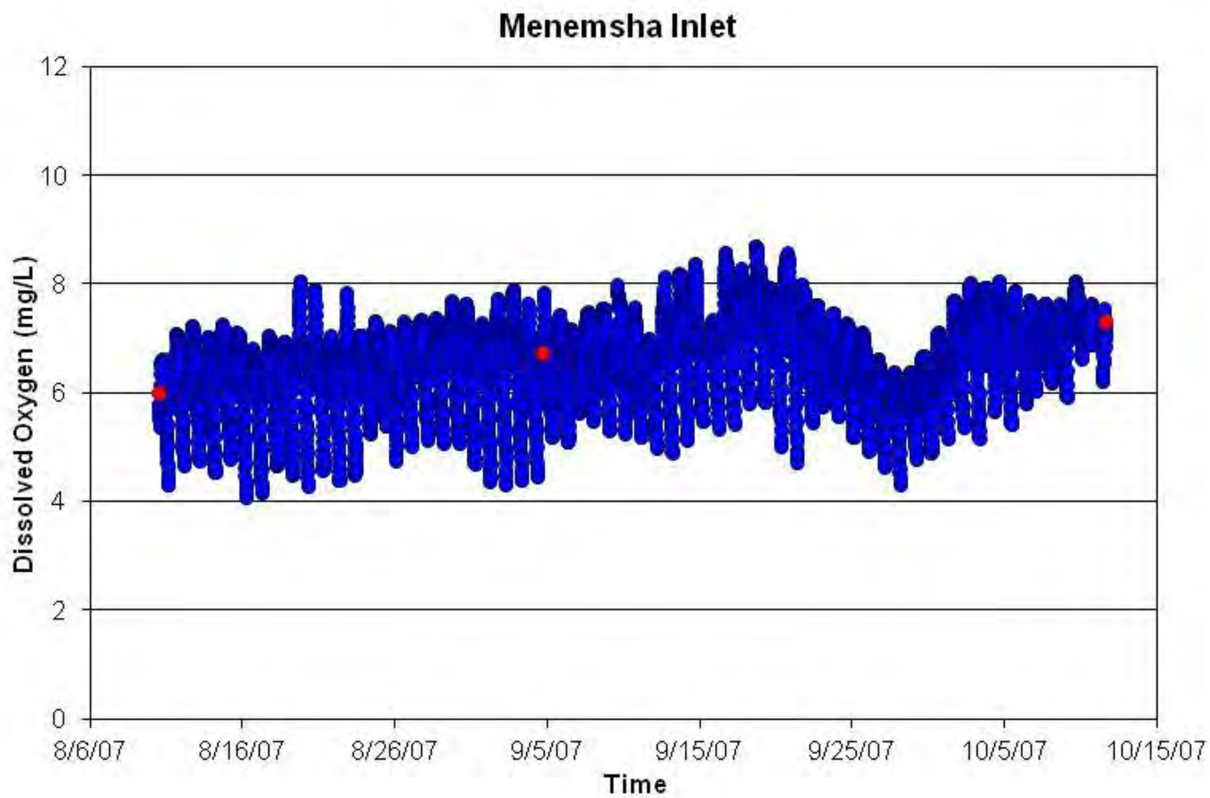

Figure VII-3. Bottom water record of dissolved oxygen at the Menemsha Inlet station, Summer 2007 (location in Figure VII-1). Calibration samples represented by red dots.

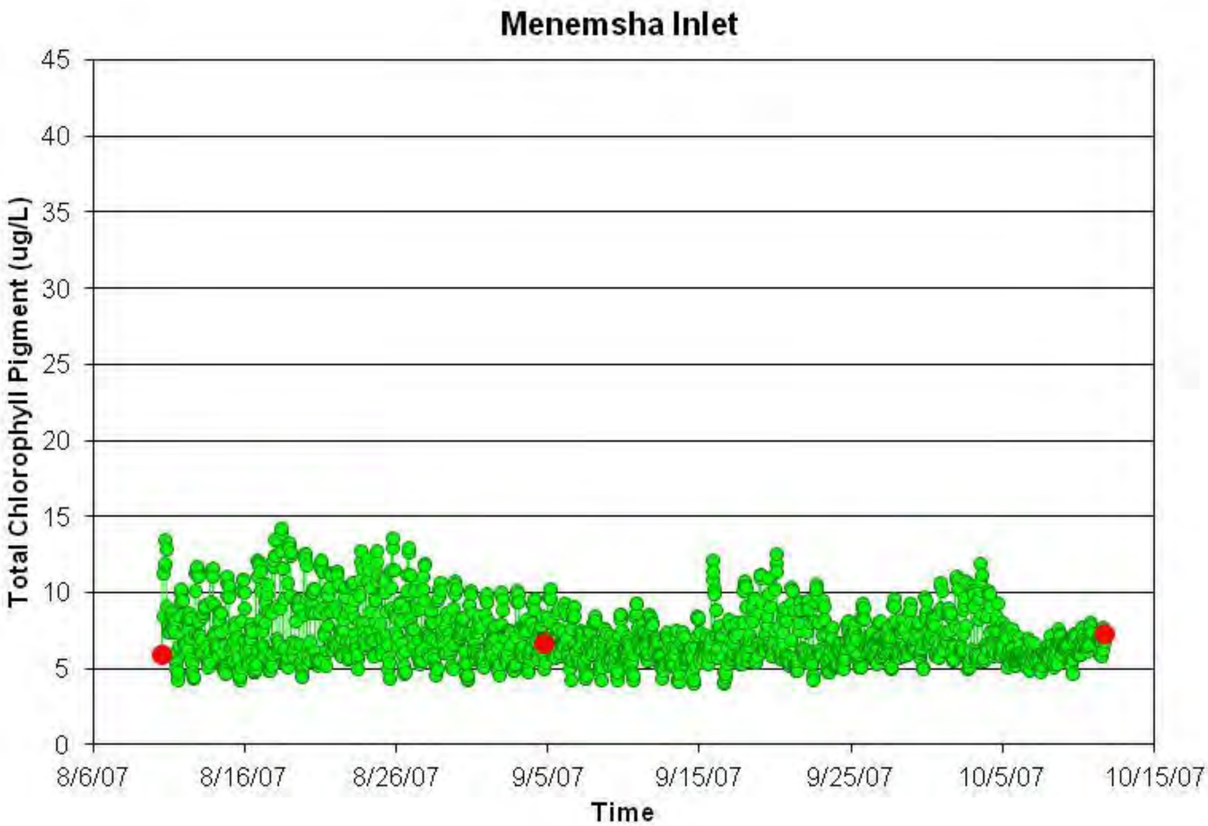

Figure VII-4. Bottom water record of Total Pigment (Chlorophyll-*a* + pheophytin) in the Menemsha Inlet station, Summer 2007 (location in Figure VII-1). Calibration samples represented as red dots.

Menemsha West Basin (Figures VII-5 and VII-6):

The Menemsha Pond Western mooring location (aka. Menemsha-Inner) is in the main basin of Menemsha Pond furthest from the tidal inlet (approximately 2 miles). The mooring was deployed on a piling adjacent to the Wampanoag hatchery and down gradient of the herring run connecting Menemsha Pond to Squibnocket Pond (Figure VII-1a). Daily excursions (maximum to minimum) in oxygen levels at this location were moderate, generally varying approximately 2 mg L^{-1}. Oxygen levels varied primarily with tide and light (diurnal cycle) as the pond exchanged water through the inlet with every tidal cycle. Lowest oxygen was generally observed in the early morning on ebbing tides. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Maximum oxygen levels did not exceed air equilibration (% air saturation), which occurs when nitrogen enrichment has stimulated phytoplankton growth and oxygen production. The moderately ranging oxygen conditions corresponded to moderate chlorophyll-a conditions at this location during the deployment period. Oxygen conditions did appear higher (6 to 8 mg L^{-1}) in the first 10 days of the deployment and lower (4 to 6 mg L^{-1}) over the following 20 days with an increase back to higher oxygen conditions as was observed in the earlier portion of the deployment. Both the moderate oxygen levels (6 to 8 mg L^{-1}), the moderate daily excursion and the moderate chlorophyll levels suggests that a moderate level of organic matter enrichment exists in this region of the pond. It is likely that the nitrogen and organic matter enriched waters entering this region from Squibnocket Pond on each ebbing tide play a role in the observed conditions.

Oxygen levels occasionally were above 6 mg L^{-1} for 77% of record and declined to <5 mg L^{-1} for only 9% of the 84 day record (Figure VII-5). Moreover, oxygen levels rarely (<1%) reached 4 mg L^{-1}, the oxygen stress threshold (Table VII-1a). The infrequent and insignificant oxygen declines were consistent with the low to moderate levels of phytoplankton biomass as measured by chlorophyll-*a*. Chlorophyll-*a* averaged 8.0 ug L^{-1} over the record, infrequently exceeding 10 ug L^{-1} (22% of record) and 15 ug L^{-1} 3% of record. Average chlorophyll-*a* conditions in this portion of the main basin were similar to average CHLA levels at the inlet mooring location and generally showed the same range (mostly 5-10 ug L^{-1}) over the entire deployment period. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality in temperate embayments. Both the extent of oxygen depletion and the levels of chlorophyll are indicative of a sub-basin with moderate nitrogen and organic matter enrichment (Table VII-2a, Figure VII-6).

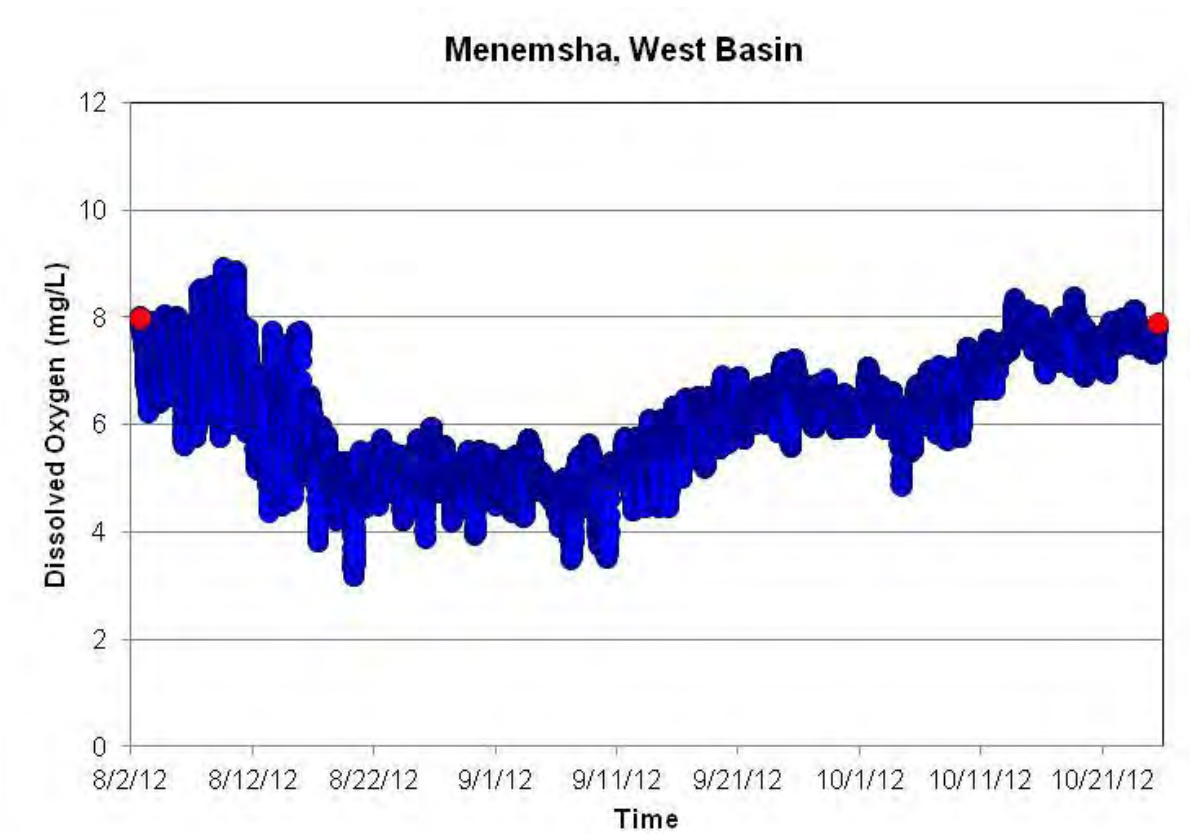

Figure VII-5. Bottom water record of dissolved oxygen recorded within the western portion of the main basin of Menemsha Pond (inner), summer 2012 (location in Figure VII-1). Calibration samples represented as red dots.

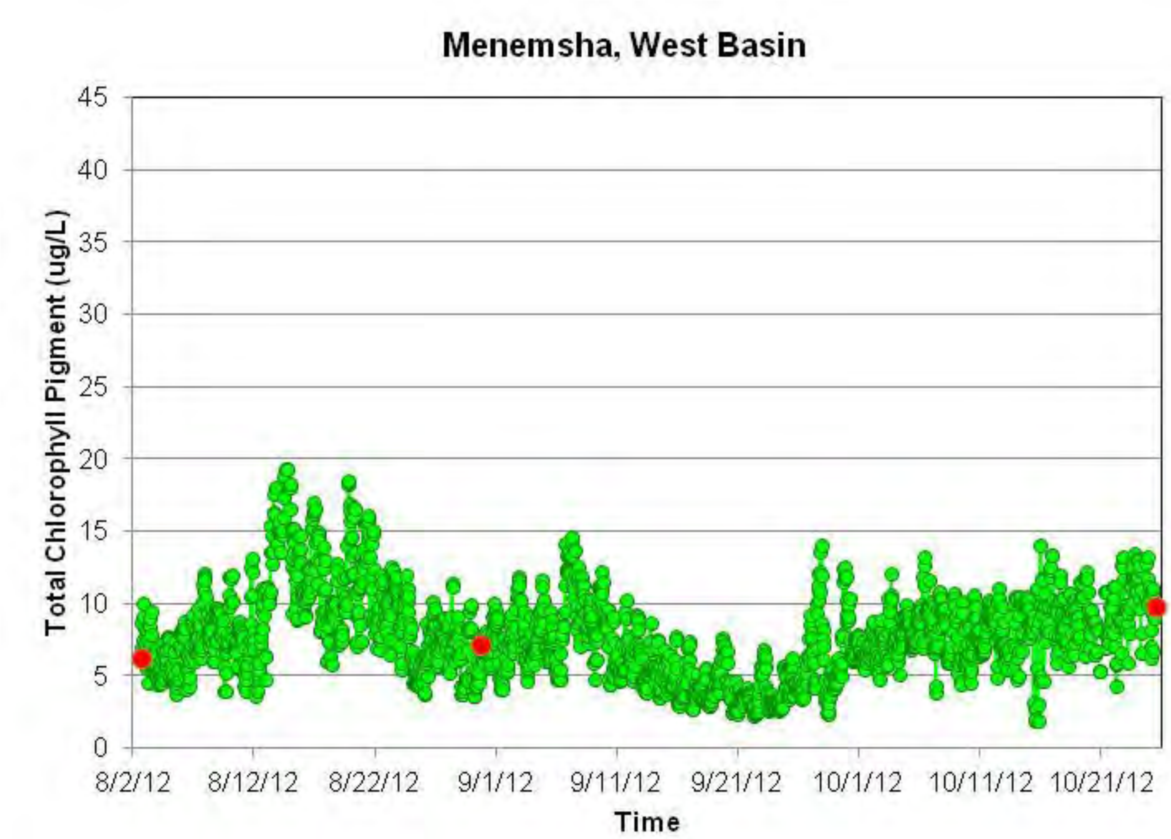

Figure VII-6. Bottom water record of Total Pigment (Chlorophyll-*a* + pheophytin) in the Menemsha West Basin (inner station), Summer 2012 (location in Figure VII-1). Calibration samples represented as red dots.

Menemsha-Nashaquitsa Pond (Figures VII-7 and VII-8):

The Nashaquitsa Pond mooring location represents the main basin of this sub-embayment to the main basin of Menemsha Pond. Nashaquitsa Pond receives water from Menemsha Pond via a narrow tidal channel. The mooring was deployed at a central location and was mounted 30cm off the bottom to characterize oxygen conditions encountered by benthic animals. Nashaquitsa Pond is a depositional basin with soft organic muds, which has lost much of its eelgrass coverage over the past 20 years (Figure VII-1a). Daily excursions (maximum to minimum) in oxygen levels at this location were similar to the main basin of Menemsha Pond and were moderate, generally varying approximately 2 mg L^{-1}. Oxygen levels varied primarily with tide and light (diurnal cycle) as the pond exchanged water with Menemsha Pond's main basin through the narrow inlet with every tidal cycle. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Maximum oxygen levels did not exceed air equilibration (% air saturation), which occurs when nutrient enrichment has stimulated phytoplankton growth and oxygen production through photosynthesis. The moderate range of oxygen variation corresponded to moderate chlorophyll a levels, averaging 8.4 ug L^{-1}, but exceeding 10 ug L^{-1} for 18% of record and supporting blooms of 25 ug L^{-1}. Both the moderate oxygen levels (5 to 9 mg L^{-1}), the moderate daily excursion and the moderate chlorophyll levels suggests that organic matter enrichment is occurring within this basin.

Oxygen levels were generally above 6 mg L^{-1} (97% of record) and never declined to less than 5 mg L^{-1} over the 64 day record (Figure VII-7). Oxygen levels within this tributary basin to the overall system were always >4 mg L^{-1}, the critical threshold for oxygen stress in an estuarine system (Table VII-1a). The infrequent oxygen declines were generally consistent with the moderate levels of phytoplankton biomass as measured by chlorophyll-*a*. Although chlorophyll-*a* levels were generally moderate and constant throughout the mooring deployment, a bloom was also observed later in the deployment lasting 7-10 days reaching levels as high as 30 ug L^{-1}. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality in temperate embayments. The observed levels of chlorophyll-*a* are generally indicative of moderate water quality in this basin, however, the phytoplankton bloom is a sign that the basin has reached a point where further nutrient enrichment, potentially magnified by low tidal flushing with higher quality water from the main basin of Menemsha Pond, will result in increasing summer phytoplankton biomass and number and duration blooms (Table VII-2a, Figure VII-8).

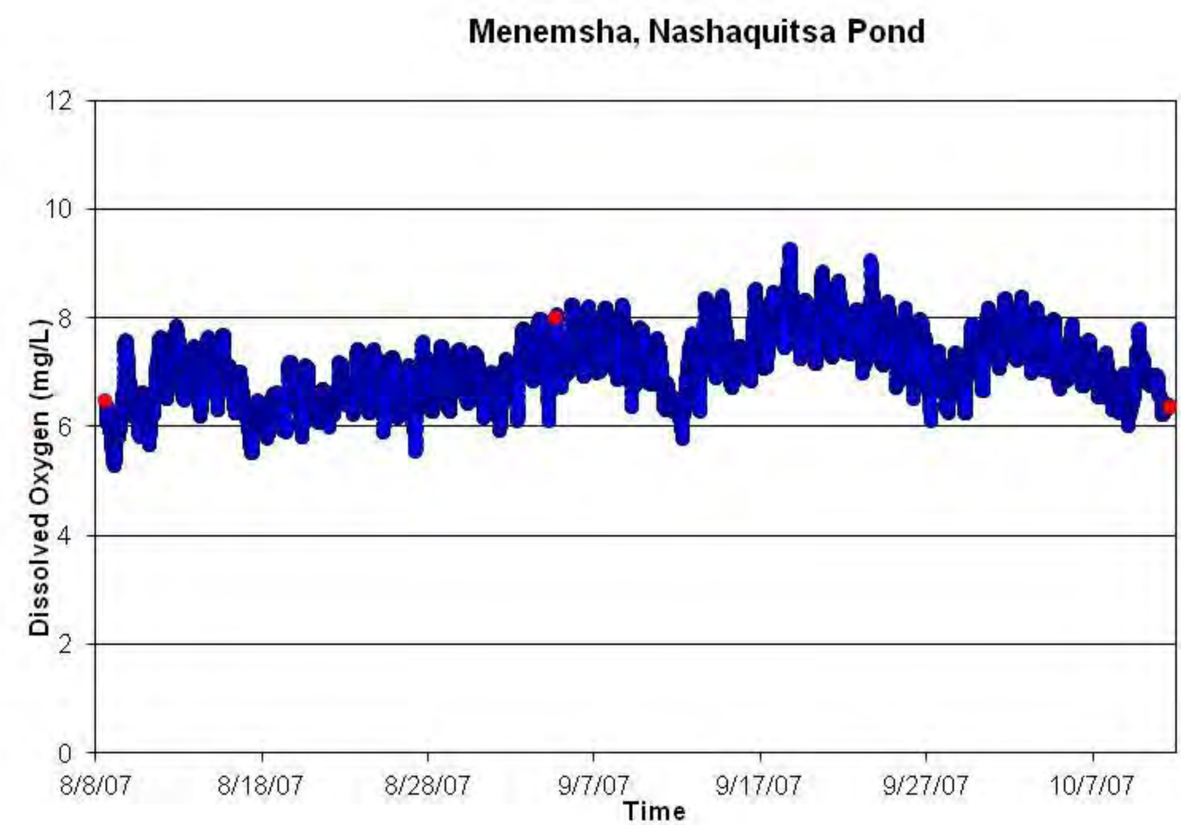

Figure VII-7. Bottom water record of dissolved oxygen within the Nashaquitsa Pond portion of Menemsha Pond, summer 2007 (Figure VII-1). Calibration samples shown as red dots.

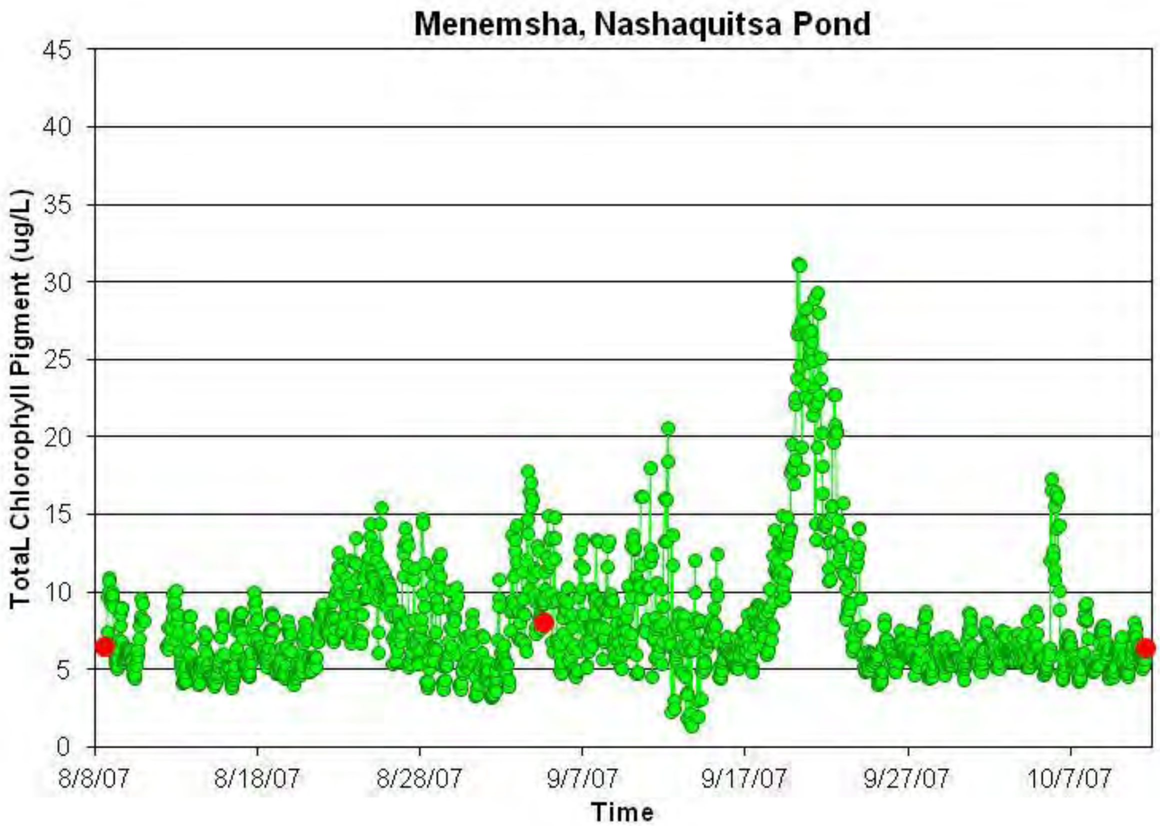

Figure VII-8. Bottom water record of Total Pigment (Chlorophyll-*a* + pheophytin) in the Nashaquitsa station, Summer 2007 (location in Figure VII-1). Calibration samples represented as red dots.

Menemsha - Stonewall Pond (Figures VII-9 and VII-10)

The Stonewall Pond mooring location was representative of the main basin of this sub-embayment to the main basin of Menemsha Pond (via Nashaquitsa Pond). Stonewall Pond receives water from Menemsha Pond through the narrow tidal channel that connects Stonewall Pond to Nashaquitsa Pond. The mooring was deployed at a central location and was mounted 30cm above the sediment surface to characterize oxygen conditions encountered by benthic animal communities (Figure VII-1a). Oxygen levels varied primarily with tide and light (diurnal cycle) as the pond exchanges water with Menemsha Pond via Nashaquitsa Pond through the narrow, shallow inlet with every tidal cycle. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Unlike the other mooring deployments in Menemsha Pond, the Stonewall Pond mooring showed larger daily excursions in oxygen levels within this tributary basin, frequently changing as much as 5 mg L^{-1} from day to night. However, maximum oxygen levels did not exceed air equilibration (% air saturation), and only infrequently reached 10 mg L^{-1}. The large daily excursions and drops to close to 2 mg L^{-1} is indicative of a system with nitrogen, organic matter enrichment and habitat impairment, potentially magnified by its tidal exchange characteristics.

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 36% and 16% of the 64 day record respectively (Figure VII-9). Moreover, oxygen levels were frequently <4 mg L^{-1}, periodically declining below 3 mg L^{-1} for 1 % and periodically to 2 mg L^{-1} over the deployment period, well below the oxygen stress threshold of 4 mg/L (Table VII-1a). The frequent and significant oxygen declines are consistent with the observed elevated phytoplankton levels, soft organic sediments which support high rates of oxygen uptake and are generally associated with periodic significant oxygen depletions. Chlorophyll-*a* averaged 10.0 ug L^{-1} over the 64 day record, was consistently >10 ug L^{-1} and >15 ug L^{-1}, 33% and 15% of time and showed multiple blooms with one exceeding 30 ug L^{-1}. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality, a level equal to the average chlorophyll-*a* observed in this basin. Both the extent of oxygen depletion and the levels of chlorophyll in conjunction with the significant phytoplankton bloom that was captured toward the end of August 2007 are indicative of a tributary sub-embayment with nitrogen and organic matter enrichment at levels associated with habitat impairment in many embayments (Table VII-2a, Figure VII-10).

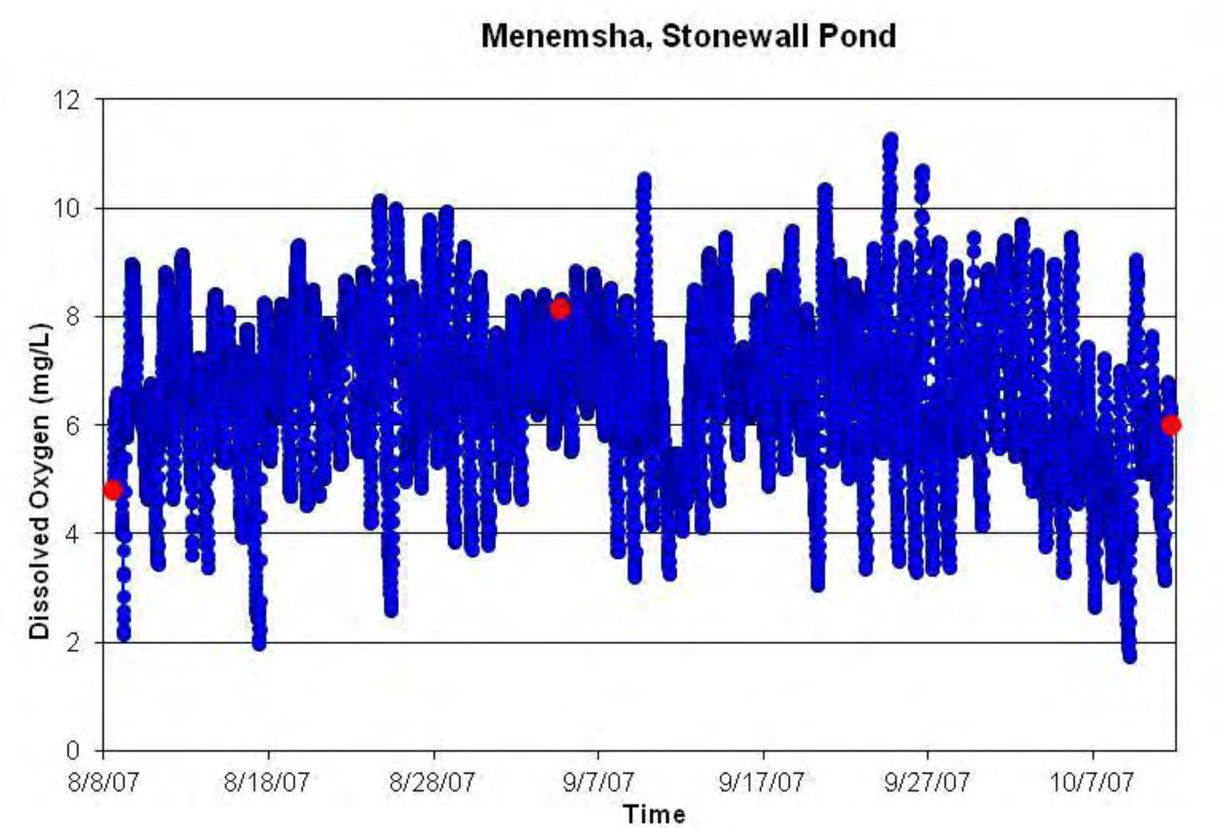

Figure VII-9. Bottom water record of dissolved oxygen within Stonewall Pond, Menemsha Pond, summer 2007 (Figure VII-1). Calibration samples shown as red dots.

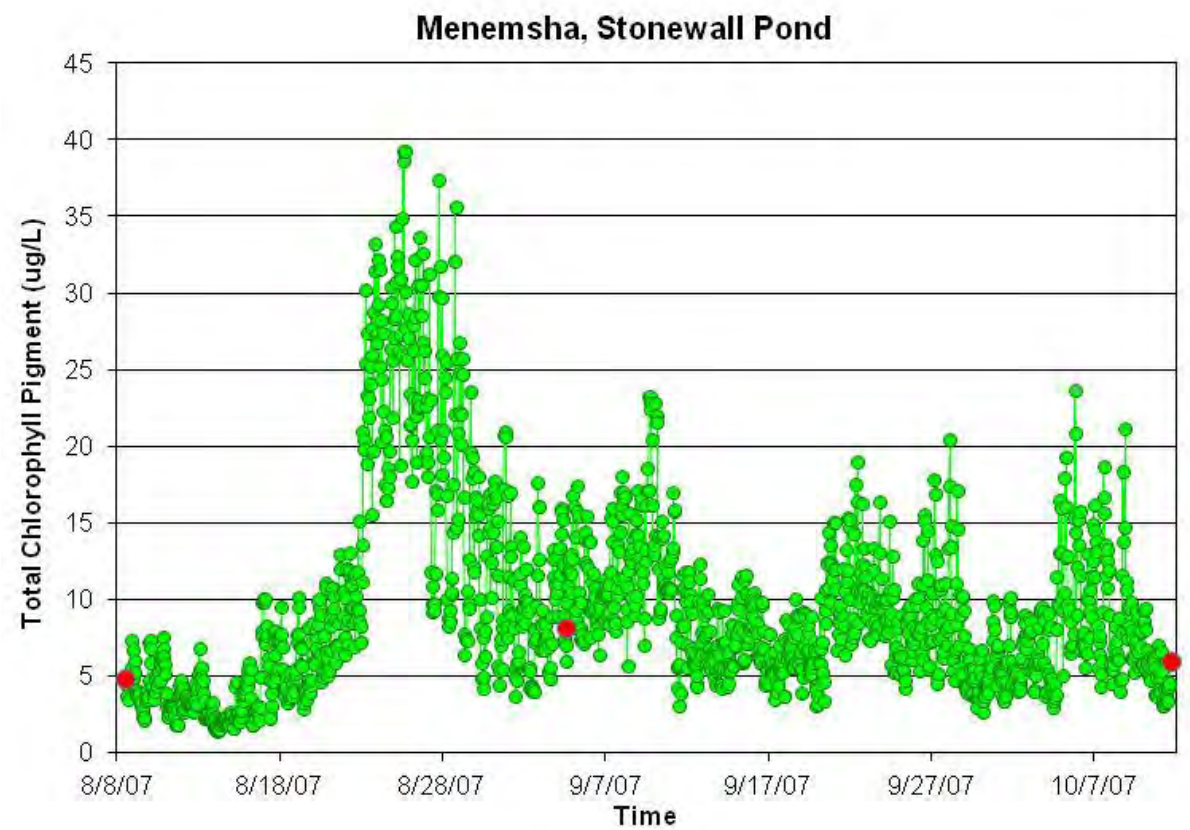

Figure VII-10. Bottom water record of Total Pigment (Chlorophyll-*a* + pheophytin) in the Stonewall Pond station, Summer 2007 (location in Figure VII-1). Calibration samples represented as red dots.

Squibnocket Pond - North (Figures VII-11 and VII-12)

The Squibnocket Pond-North mooring was located within the upper most portion of the basin approximately 500 feet from the channel that connects Squibnocket Pond to Menemsha Pond (Figure VII-1b). Daily excursions (maximum to minimum) in oxygen levels at this location were moderate, generally varying approximately 2 mg L^{-1}. Oxygen levels varied primarily with light (diurnal cycle) and to a lower degree tide as the pond has limited exchange of water with Menemsha Pond during most tidal cycles via the herring run. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Maximum oxygen levels did not exceed air equilibration (% air saturation), which can occur when nutrient enrichment has stimulated phytoplankton growth and oxygen production from photosynthesis. The moderately ranging oxygen conditions corresponded to relatively low chlorophyll-a conditions at this location during the deployment period. Both the moderate oxygen levels (6 to 8 mg L^{-1}), the moderate daily excursion and the relatively low chlorophyll levels suggests that significant organic matter enriched conditions are not extant in this region of the basin during the measurement period. It is likely that these conditions result from the site's proximity to the relatively high quality waters entering from Menemsha Pond on each flooding tide.

Oxygen levels were generally above 6 mg L^{-1} (96% of record) and only infrequently declined to less than 5 mg L^{-1} for only 1% of the 65 day record (Figure VII-3). Oxygen levels at this site in the upper most portion of the Squibnocket Pond sub-system were always >4 mg L^{-1}, the critical threshold for oxygen stress in an estuarine system (Table VII-1a). The low level of oxygen depletion are generally consistent with the moderate to low levels of phytoplankton biomass as measured by chlorophyll-*a* for the complete deployment period. Chlorophyll-*a* averaged 7.3 ug L^{-1} over the record and exceeded 10 ug L^{-1} 13% of the deployment period and rarely reached 15 ug L^{-1}. The chlorophyll-*a* levels were generally low and constant throughout the mooring deployment, however, they were slightly higher in the first two weeks of the deployment (slightly above 10 ug L^{-1}) whereas levels were generally below 10 ug L^{-1} for the remainder of the record. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality in temperate embayments, a level infrequently surpassed by the average chlorophyll-*a* observed in this portion of Squibnocket Pond. These levels of chlorophyll-*a* are indicative of relatively good quality water entering the main basin of Squibnocket Pond from Menemsha Pond (Table VII-2b, Figure VII-12).

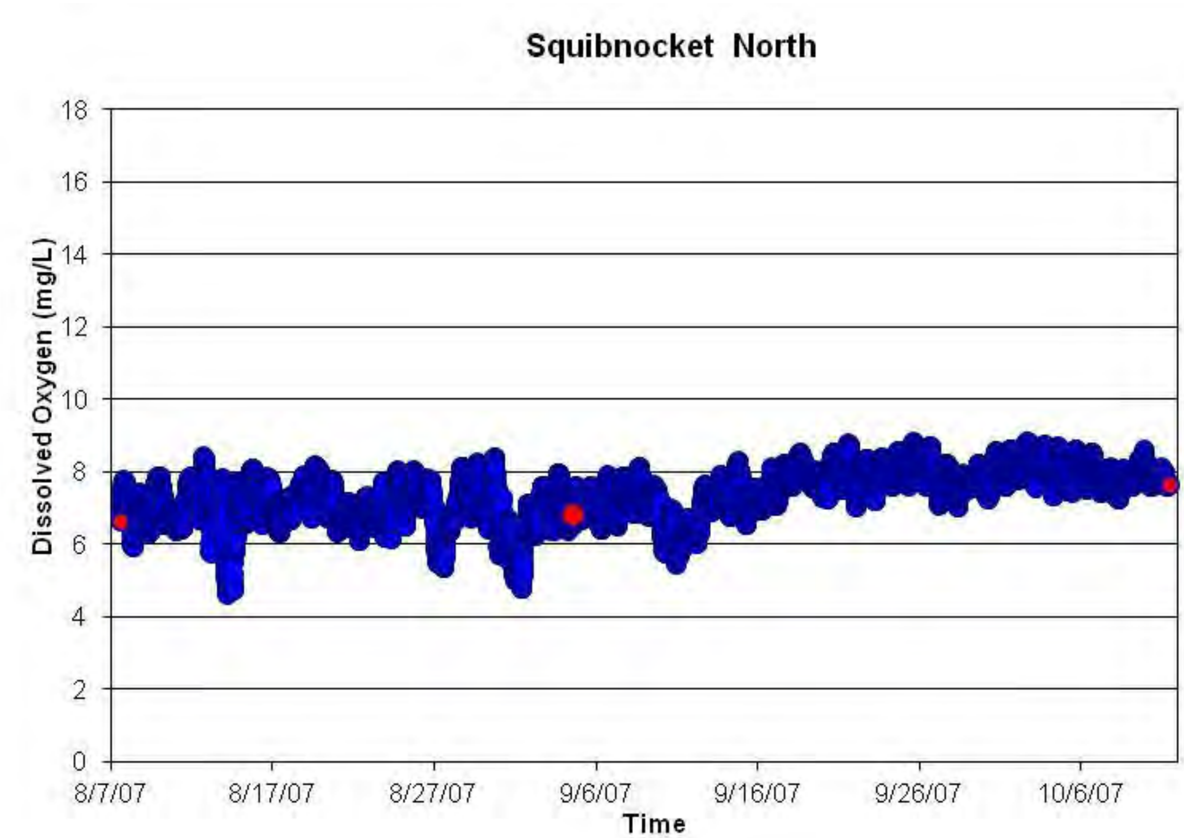

Figure VII-11. Bottom water record of dissolved oxygen within Squibnocket Pond, North mooring location, summer 2007 (Figure VII-1). Calibration samples shown as red dots.

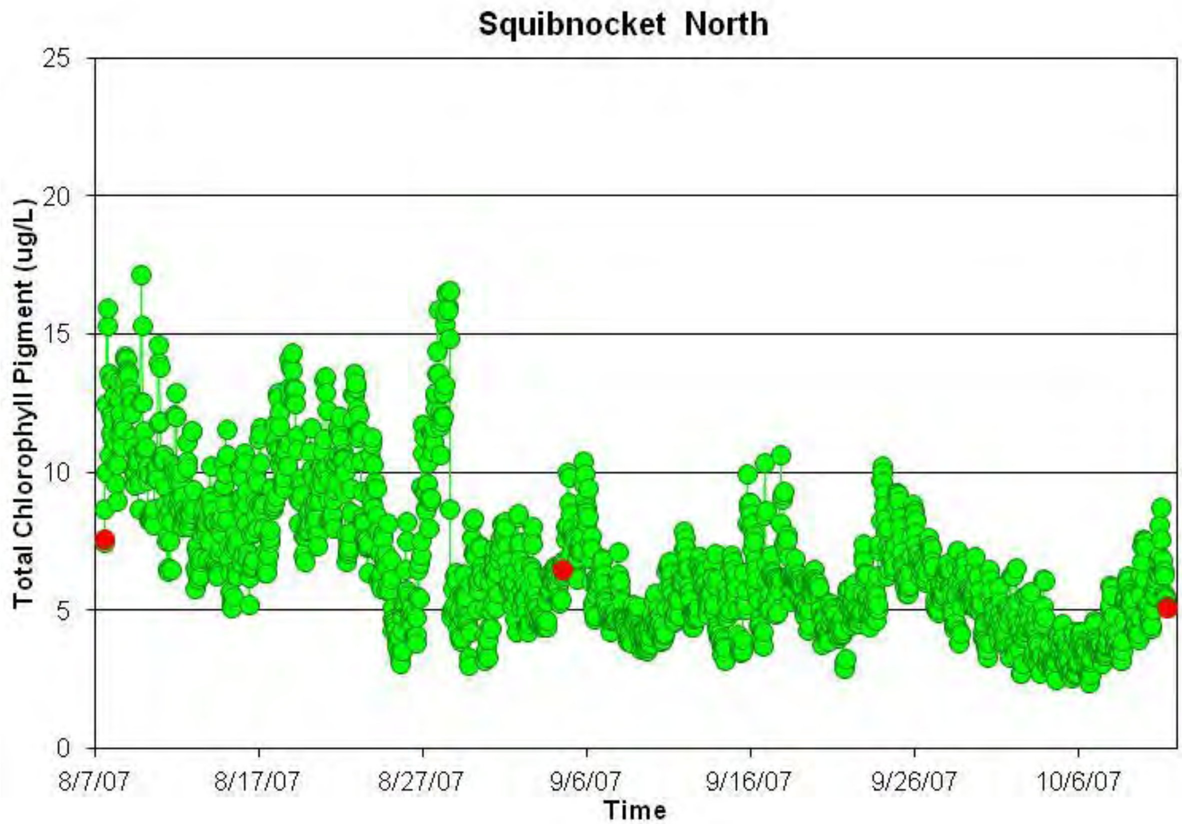

Figure VII-12. Bottom water record of Total Pigment (Chlorophyll-*a* + pheophytin) within the Squibnocket Pond - North location, summer 2007 (location in Figure VII-1). Calibration samples shown as red dots.

Squibnocket Pond - South (Figures VII-13 and VII-14)

The Squibnocket Pond-South mooring is representative of the conditions within the southern region of the main basin of this large sub-embayment and is approximately one mile away from the herring run connecting Squibnocket Pond to Menemsha Pond. The mooring was deployed 30cm above the sediment surface to characterize oxygen conditions encountered by benthic animal communities with little tidal effect due to the limited exchange of water with Menemsha Pond. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Unlike the other mooring deployments in Menemsha Pond, the Squibnocket Pond-South mooring showed larger daily excursions in oxygen levels within this sector of the pond basin, frequently changing as much as 8 mg L^{-1} from day to night and dropping below 2 mg L^{-1}, significantly less than the 3.8 mg L^{-1} level that indicates habitat impairment. Additionally, maximum oxygen levels did exceed air equilibration (% air saturation), and frequently exceeded 10 mg L^{-1}, even reaching as high as 12-14 mg L^{-1} for short portions of the record. The large daily excursions and drops to close to 2 mg L^{-1} is indicative of a system with organic matter enrichment and habitat impairment, likely aggravated by low exchange and circulation.

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 50% and 37% of the 26 day record respectively (Figure VII-13). Moreover, oxygen levels were frequently <4 mg L^{-1} (26%), periodically declining below 3 mg L^{-1} for 16 % of the deployment period, well below the oxygen stress threshold of 4 mg/L (Table VII-1b). The frequent and significant oxygen declines are indicative of high levels of organic matter enrichment, however, not entirely consistent with the moderate to somewhat low levels of phytoplankton biomass as measured by chlorophyll-*a*. Chlorophyll-*a* averaged 6.2 ug L^{-1} over the 64 day record and was only infrequently >15 ug L^{-1} 7% of deployment period. However, the sediments of this region of the basin supported a dense microalgal photosynthetic mat which would contribute to the observed oxygen production/consumption. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality, a level above the average chlorophyll-*a* observed in this sector of the basin. While the levels of chlorophyll appear within a generally acceptable range, the wide ranging oxygen levels dropping to hypoxic levels is concerning and indicative of an estuarine reach that may be affected by significant organic matter enrichment at levels associated with habitat impairment in many embayments of southeastern (Table VII-2b, Figure VII-14).

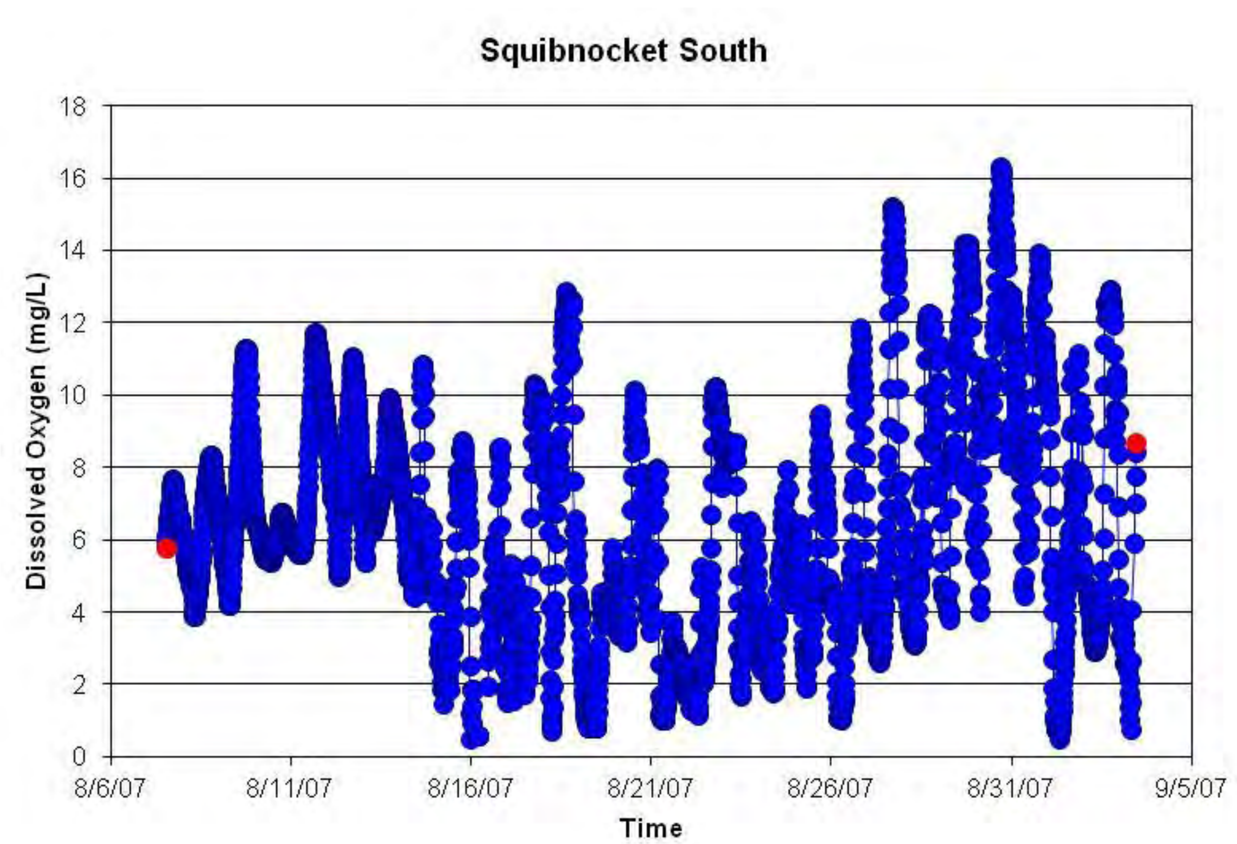

Figure VII-13. Bottom water record of dissolved oxygen within Squibnocket Pond, South mooring location, summer 2007 (Figure VII-1). Calibration samples shown as red dots.

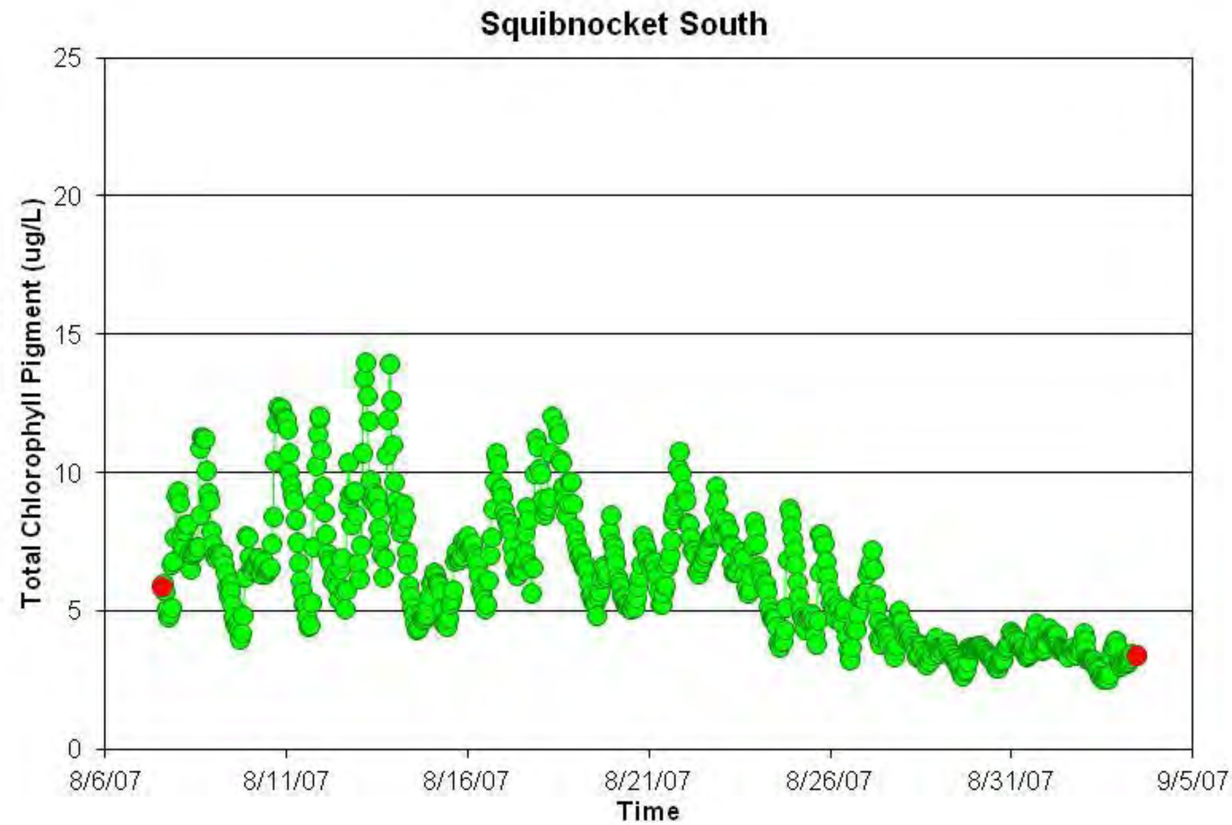

Figure VII-14. Bottom water record of Total Pigment (Chlorophyll-*a* + pheophytin) within the Squibnocket Pond-South mooring location, summer 2007 (location in Figure VII-1). Calibration samples shown as red dots.

Squibnocket Pond - East (Figures VII-15 and VII-16)

The Squibnocket Pond-East mooring is representative of the conditions within the eastern region of Squibnocket Pond and is approximately one mile away from the herring run connecting Squibnocket Pond to Menemsha Pond. The mooring was deployed at a central location in the eastern portion of the basin and was mounted 30cm above the sediment surface to characterize oxygen conditions encountered by benthic animal communities (Figure VII-1b). Oxygen levels varied primarily with light (diurnal cycle) with little tidal influence. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Unlike the other mooring deployments in Menemsha Pond, the Squibnocket Pond-East mooring showed larger daily excursions in oxygen levels within this sector of the pond basin, frequently changing as much as 8 mg L^{-1} from day to night and dropping below 2 mg L^{-1}, significantly less than the 3.8 mg L^{-1} level that indicates habitat impairment. Additionally, maximum oxygen levels did exceed air equilibration (% air saturation), and frequently exceeded 10 mg L^{-1}, even reaching as high as 12-14 mg L^{-1} for short portions of the record. The large daily excursions and drops to close to 2 mg L^{-1} is indicative of a system with organic matter enrichment and habitat impairment, likely aggravated by low exchange and circulation.

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 50% and 37% of the 64 day record respectively (Figure VII-13). Moreover, oxygen levels were frequently <4 mg L^{-1} (26%), periodically declining below 3 mg L^{-1} for 16 % of the deployment period, well below the oxygen stress threshold of 4 mg/L (Table VII-1b). The frequent and significant oxygen declines are indicative of high levels of organic matter enrichment. Oxygen conditions are consistent with the observed moderate levels of phytoplankton biomass and high macroalgal accumulations in this region of Squibnocket Pond. The dense algal coverage and moderate chlorophyll-*a* (average 6.2 ug L^{-1} over the 64 day record) combine to generate the observed oxygen field. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality, a level above the average chlorophyll-*a* observed in this sector of the basin. While the levels of chlorophyll appear within a generally acceptable range, the wide ranging oxygen levels dropping to hypoxic levels is concerning and indicative of an estuarine reach that may be affected by significant organic matter enrichment at levels associated with habitat impairment in many embayments of southeastern MA. (Table VII-2b, Figure VII-14).

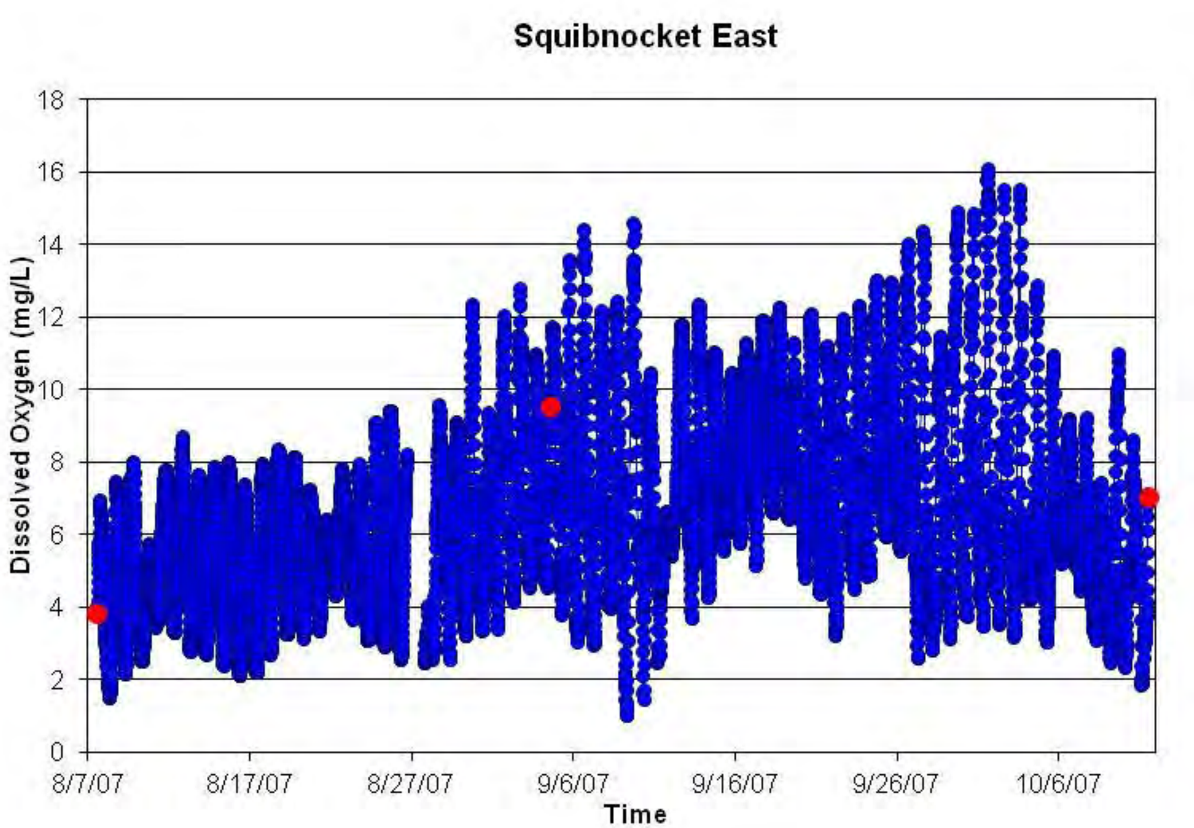

Figure VII-15. Bottom water record of dissolved oxygen within Squibnocket Pond, East mooring location, summer 2007 (Figure VII-1). Calibration samples shown as red dots.

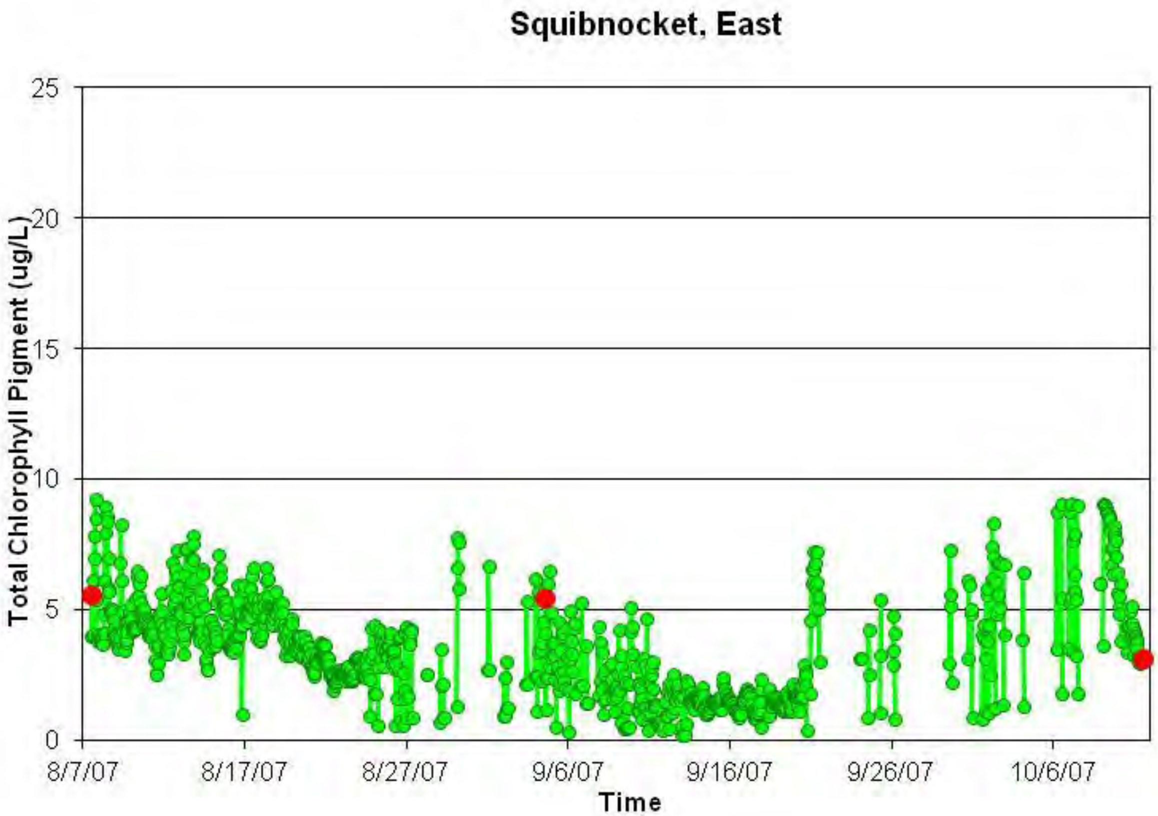

Figure VII-16. Bottom water record of Total Pigment (Chlorophyll-*a* + pheophytin) within the Squibnocket Pond - East mooring location, summer 2007 (location in Figure VII-1). Calibration samples shown as red dots.

Squibnocket Pond - West (Figures VII-17 and VII-18)

The Squibnocket Pond-West mooring is representative of conditions within the western sub-basin of Squibnocket Pond and is approximately one mile away from the herring run connecting Squibnocket Pond to Menemsha Pond. The mooring was deployed 30cm above the sediment surface to characterize oxygen conditions encountered by benthic animal communities in a depositional area of soft organic rich sediments (Figure VII-1b). Similar to other mooring locations in the Squibnocket Pond basin, oxygen levels varied primarily with light (diurnal cycle) with little tidal influence. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Unlike the other mooring deployments in Squibnocket Pond, the Squibnocket Pond-West mooring showed smaller daily excursions in oxygen levels within this sector of the pond basin, frequently only changing 2-4 mg L^{-1} from day to night. Nevertheless, oxygen levels at the beginning of the deployment period did appear well below the 4 mg L^{-1} level that indicates habitat impairment, dropping well below 2 mg L^{-1} and existing below 3.0 mg L^{-1} 4% of the deployment period. Additionally, maximum oxygen levels did exceed air equilibration (% air saturation) and occasionally approached/exceeded 10 mg L^{-1} for short portions of the record. The large daily excursions and drops to close to 2 mg L^{-1} is indicative of a system with organic matter enrichment and habitat impairment, likely aggravated by low exchange and circulation.

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 29% and 15% of the 84 day record respectively (Figure VII-17). Moreover, oxygen levels commonly declined to <4 mg L^{-1} (8%), periodically declining below 3 mg L^{-1} for 4 % of the deployment period, well below the oxygen stress threshold of 4 mg/L (Table VII-1b). These oxygen declines are indicative of organic matter enrichment and are consistent with the moderate to high levels of phytoplankton biomass as measured by chlorophyll-*a* and high rates or oxygen uptake in the water column and sediments. While chlorophyll-*a* averaged 7.6 ug L^{-1} over the 84 day record, there were clear periods at the beginning and end of the record that did show presence of phytoplankton blooms and levels that did frequently exceed >10 ug L^{-1} 24% of deployment period and exceeded >15 ug L^{-1} 7% of the time. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired water quality related to nitrogen and organic matter enrichment, a level above the average chlorophyll-*a* typically observed in this sector of the basin. The levels of dissolved oxygen generally show some impairment consistent with the wide range of chlorophyll-a levels and the observed blooms. These features are concerning and indicative of an estuarine reach that is beyond its nitrogen threshold, one that is affected by significant organic matter enrichment at levels associated with habitat impairment in many embayments of southeastern MA. (Table VII-2b, Figure VII-18).

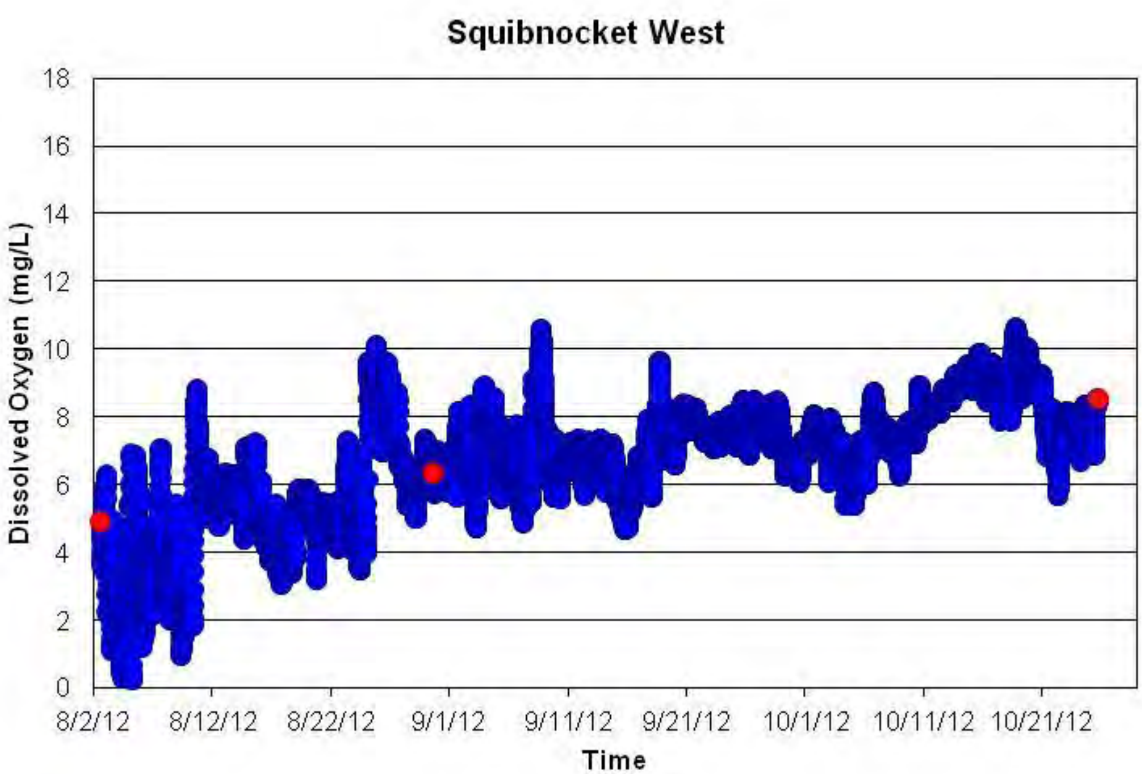

Figure VII-17. Bottom water record of dissolved oxygen within Squibnocket Pond, West mooring location, summer 2012 (Figure VII-1). Calibration samples shown as red dots.

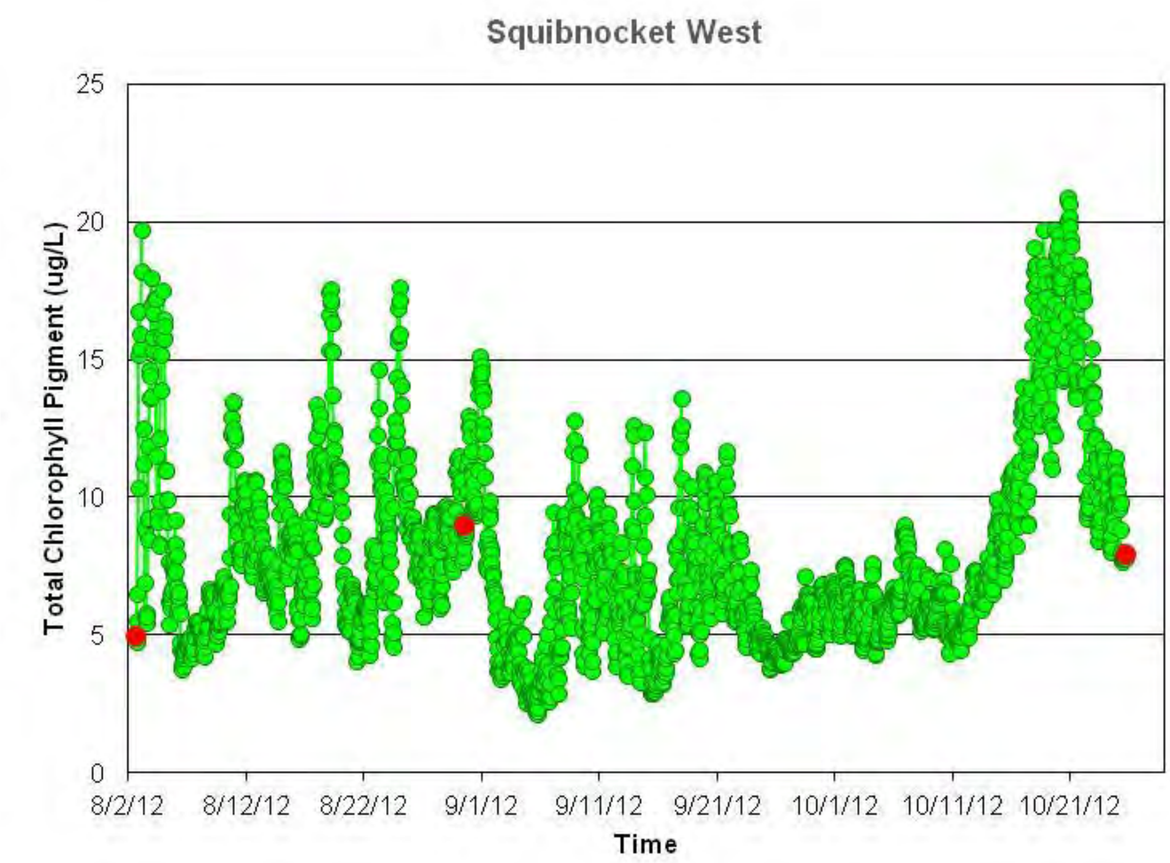

Figure VII-18. Bottom water record of Total Pigment (Chlorophyll-*a* + pheophytin) within the Squibnocket Pond - West mooring location, summer 2012 (location in Figure VII-1). Calibration samples shown as red dots.

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

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Menemsha Inlet	**8/8/2007**	**10/11/2007**	**61.8**	**23%**	**4%**	**0%**	**0%**
			Mean	0.19	0.10	NA	NA
			Min	0.01	0.01	0.00	0.00
			Max	0.45	0.17	0.00	0.00
			S.D.	0.11	0.04	NA	NA
Menemsha, Nashaquitsa Pond	**8/8/2007**	**10/11/2007**	**64.1**	**3%**	**0%**	**0%**	**0%**
			Mean	0.14	NA	NA	NA
			Min	0.01	0.00	0.00	0.00
			Max	0.67	0.00	0.00	0.00
			S.D.	0.17	NA	NA	NA
Menemsha, Stone Wall Pond	**8/8/2007**	**10/11/2007**	**64.1**	**36%**	**16%**	**5%**	**1%**
			Mean	0.35	0.20	0.13	0.15
			Min	0.04	0.01	0.02	0.06
			Max	1.51	0.63	0.42	0.26
			S.D.	0.24	0.14	0.10	0.10
Menemsha, West Basin	**7/31/2012**	**10/26/2012**	**83.9**	**23%**	**9%**	**0%**	**0%**
			Mean	1.74	0.22	0.07	NA
			Min	0.05	0.01	0.02	0.00
			Max	16.96	0.69	0.17	0.00
			S.D.	5.05	0.19	0.06	NA

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

Mooring Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Menemsha Inlet	**8/8/2007**	**10/11/2007**	**62.0**	**95%**	**10%**	**0%**	**0%**	**0%**
Mean Chl Value = 7.3 ug/L			**Mean**	1.73	0.14	NA	NA	NA
			Min	0.04	0.04	0.00	0.00	0.00
			Max	13.25	0.25	0.00	0.00	0.00
			S.D.	2.35	0.06	NA	NA	NA
Menemsha, Nashaquitsa Pond	**8/8/2007**	**10/11/2007**	**62.8**	**87%**	**18%**	**5%**	**3%**	**1%**
Mean Chl Value = 8.4 ug/L			**Mean**	0.85	0.22	0.22	0.34	0.09
			Min	0.04	0.04	0.04	0.04	0.04
			Max	7.04	3.79	1.50	0.75	0.13
			S.D.	1.36	0.52	0.39	0.27	0.03
Menemsha, Stone Wall Pond	**8/8/2007**	**10/11/2007**	**64.1**	**78%**	**33%**	**15%**	**8%**	**4%**
Mean Chl Value = 10.0 ug/L			**Mean**	0.82	0.23	0.19	0.22	0.15
			Min	0.04	0.04	0.04	0.04	0.04
			Max	9.54	4.25	4.13	0.71	0.54
			S.D.	1.66	0.47	0.57	0.20	0.14
Menemsha, West Basin	**7/31/2012**	**10/26/2012**	**71.1**	**93%**	**22%**	**3%**	**0%**	**0%**
Mean Chl Value = 8.0 ug/L			**Mean**	0.89	0.20	0.15	NA	NA
			Min	0.04	0.04	0.04	0.00	0.00
			Max	11.75	1.67	0.46	0.00	0.00
			S.D.	1.66	0.27	0.13	NA	NA

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

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Squibnocket East	**8/7/2007**	**10/11/2007**	**63.9**	**47%**	**31%**	**17%**	**6%**
			Mean	0.43	0.30	0.23	0.15
			Min	0.01	0.01	0.02	0.02
			Max	1.57	0.71	0.56	0.42
			S.D.	0.25	0.19	0.13	0.10
Squibnocket West	**8/2/2012**	**10/25/2012**	**84.1**	**29%**	**15%**	**8%**	**4%**
			Mean	0.47	0.36	0.22	0.16
			Min	0.01	0.01	0.01	0.03
			Max	7.10	1.94	1.20	0.66
			S.D.	1.08	0.47	0.29	0.16
Squibnocket South	**8/7/2007**	**9/3/2007**	**26.4**	**50%**	**37%**	**26%**	**16%**
			Mean	0.33	0.25	0.21	0.16
			Min	0.01	0.01	0.01	0.03
			Max	1.51	1.16	1.15	0.66
			S.D.	0.35	0.26	0.23	0.15
Squibnocket North	**8/7/2007**	**10/11/2007**	**64.7**	**4%**	**1%**	**0%**	**0%**
			Mean	0.18	0.11	NA	NA
			Min	0.01	0.08	0.00	0.00
			Max	0.78	0.13	0.00	0.00
			S.D.	0.22	0.02	NA	NA

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

Mooring Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Squibnocket East	**8/7/2007**	**10/11/2007**	**40.8**	**20%**	**0%**	**0%**	**0%**	**0%**
Mean Chl Value = 3.5 ug/L			Mean	0.14	NA	NA	NA	NA
			Min	0.04	0.00	0.00	0.00	0.00
			Max	0.96	0.00	0.00	0.00	0.00
			S.D.	0.16	NA	NA	NA	NA
Squibnocket West	**8/2/2012**	**10/25/2012**	**71.1**	**96%**	**24%**	**7%**	**0%**	**0%**
Mean Chl Value = 7.6 ug/L			Mean	1.58	0.50	0.37	0.21	NA
			Min	0.04	0.04	0.04	0.21	0.00
			Max	13.29	4.96	0.83	0.21	0.00
			S.D.	2.66	0.83	0.23	NA	NA
Squibnocket South	**8/7/2007**	**9/3/2007**	**26.8**	**64%**	**7%**	**0%**	**0%**	**0%**
Mean Chl Value = 6.2 ug/L			Mean	1.32	0.19	NA	NA	NA
			Min	0.04	0.04	0.00	0.00	0.00
			Max	4.75	0.46	0.00	0.00	0.00
			S.D.	1.58	0.11	NA	NA	NA
Squibnocket North	**8/7/2007**	**10/11/2007**	**65.0**	**71%**	**13%**	**1%**	**0%**	**0%**
Mean Chl Value = 7.3 ug/L			Mean	0.70	0.23	0.10	NA	NA
			Min	0.04	0.04	0.04	0.00	0.00
			Max	17.58	1.17	0.25	0.00	0.00
			S.D.	2.21	0.28	0.09	NA	NA

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass distribution and analysis of historical data was conducted for the Menemsha Pond and Squibnocket Pond Embayment System by the MassDEP Eelgrass Mapping Program as part of the MEP technical effort. Field surveys, however, were limited to Menemsha Pond due to the vessel access constraints imposed by Squibnocket Pond. Field surveys by the MassDEP were conducted in 1995, 2001 and 2006, to provide on-site validation of aerial mapping results. Additional field observations were made during summer and fall 2006 by the SMAST/MEP Technical Team. Analysis of available aerial photography from 1951 was conducted to reconstruct the eelgrass distribution prior to the present level of development across the watershed, however this coverage could not be verified and was not used for threshold analysis for Squibnocket Pond. The primary use of the eelgrass data within the MEP approach is to indicate: (a) if eelgrass once or currently colonizes a basin and (b) quantify any large-scale system-wide shifts in distribution. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 to 2006 (Figure VII-19). This temporal information can be used to determine the stability of the eelgrass community in many systems.

All of the available information on eelgrass within the Menemsha Creek/Channel, Menemsha Pond, Nashaquitsa Pond and Stonewall Pond portions of the estuarine system indicates that these basins supported large system-wide eelgrass coverage as recently as 1995. However, although the system continues to support significant eelgrass beds, there has been a clear decline in acreage over the past 20 years. The absence of significant eelgrass habitat within Squibnocket Pond is consistent with its structure, tidal flushing and brackish waters and indicates that benthic infauna habitat is the focal resource for assessment of impairment by nitrogen enrichment in that basin, while eelgrass habitat should be the focus within Menemsha-Nashaquitsa-Stonewall Pond basins.

Temporal changes in eelgrass distribution show stable beds and coverage within Menemsha Creek and Channel as is expected given its proximity to the system's inlet where high quality low nitrogen waters are exchanged with the Atlantic Ocean twice a day. Within the main basin of Menemsha Pond, the 1995-2006 surveys show a slight loss from the deeper waters of the deep basin (southern portion) and relatively stable fringing beds colonizing the shallow margins of the deep basin and the shallow northern half of the main basin. In contrast, Nashaquitsa Pond and Stonewall Pond show significant losses in eelgrass coverage, with complete loss in Stonewall Pond (by 2006) and a near complete loss in Nashaquitsa Pond. Eelgrass decline in the Nashaquitsa basin (since 1995) follows the pattern diagnostic of nitrogen enrichment. The initial loss was from the deeper waters in the central basin first leaving only fringing beds, then a narrowing of the fringing beds and loss entirely from the inner reach. At present only narrow fringing beds occur in the 1/3 of the Nashaquitsa Basin nearest its opening to the main basin of Menemsha Pond which is its highest flushed region. Sediments in these 2 smaller basins are mainly soft muds with only a thin oxidized surface and in some cases fluid sulfidic muds, consistent with organic matter enrichment. As noted below, the benthic infauna in these basins is also consistent with a transitional environment due to organic matter enrichment. In contrast, the sediments in eelgrass areas of Menemsha Pond and Channel are medium to coarse sands with an oxidized surface layer and even the deep basin of Menemsha Pond with fine grained consolidated sediments presents an oxidized surface.

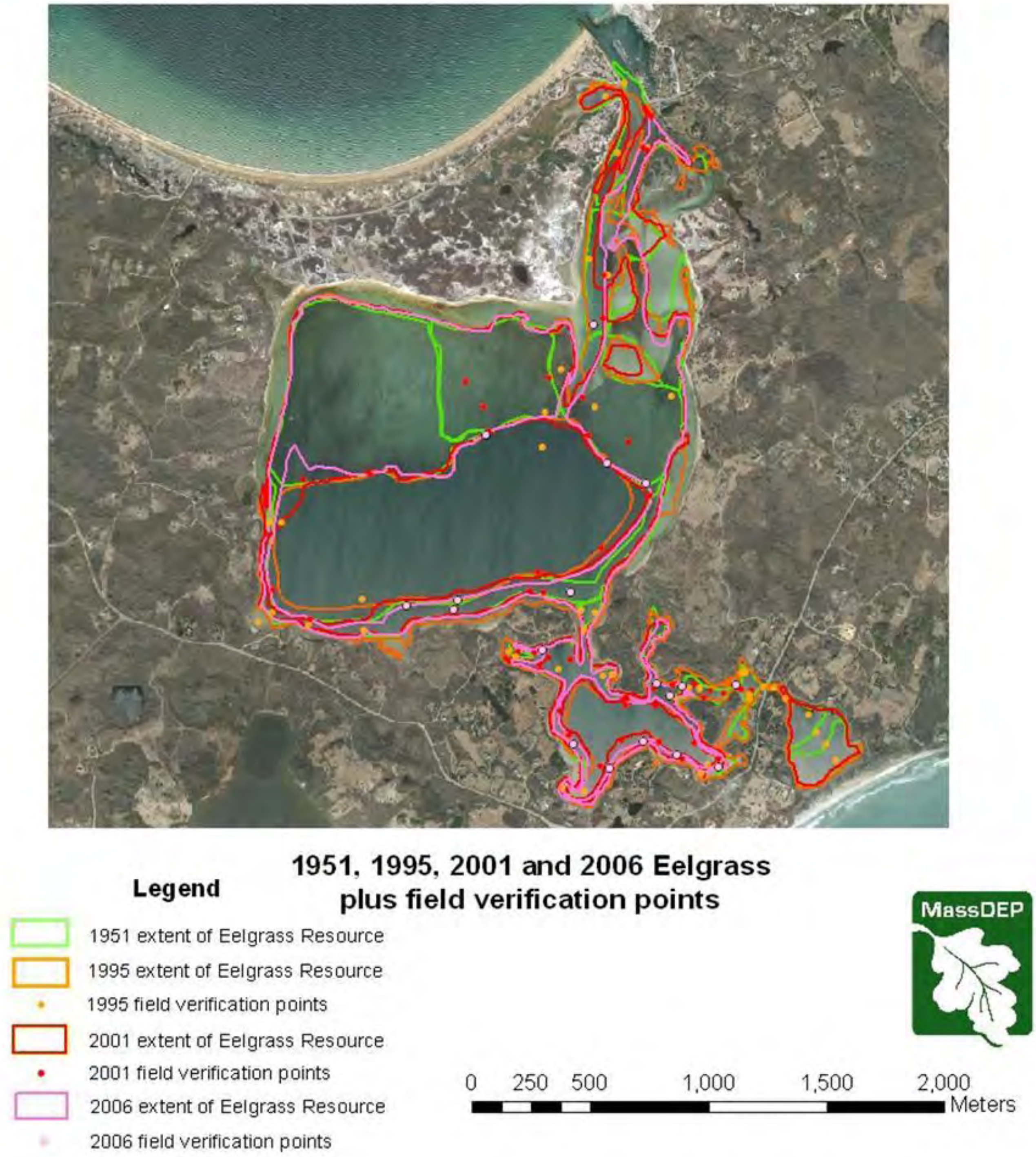

Figure VII-19. Eelgrass bed distribution in the Menemsha Pond portion of the embayment system. 1951 beds delineated using aerial photography are circumscribed by the green outline and beds delineated in 2006 using underwater video surveying are outlined in pink. Field verification points represented by dots (map from the MassDEP Eelgrass Mapping Program). No eelgrass surveying was conducted by MassDEP in Squibnocket Pond in 1995, 2001 or 2006. SMAST-MEP diver surveys did not indicate any eelgrass in Squibnocket Pond in 2006.

The observed pattern of loss of eelgrass coverage from deeper water areas to shallower water areas is typical of loss resulting from nitrogen enrichment through increased turbidity and decreased light penetration, as summer phytoplankton biomass increases. Average total pigment levels are moderate to high, 8.4 ug L^{-1} and 10.0 ug L^{-1} in Nashaquitsa Pond and Stonewall Pond, respectively. Moreover, the water is sufficiently deep (2.5 – 3.0 m) for this to limit light penetration to the bottom, restricting eelgrass habitat to the shallow areas. The loss of eelgrass appears to result mainly from decreased light penetration (from increased phytoplankton and epiphytes on eelgrass) as significant macroalgal accumulations were not observed in any basin within the Menemsha-Squibnocket Pond Embayment System. While the Menemsha-Squibnocket Pond Embayment System does support some of the highest quality eelgrass habitat associated with its generally highest water quality among southeastern Massachusetts Estuaries, the recent apparent gradual decline in eelgrass habitat in the inner basins tributary to Menemsha Pond and slight decline in Menemsha Pond's deep basin indicates that this system is just beyond its threshold level of nitrogen enrichment and further increases in nitrogen loading will almost certainly drive a progressive and potentially significant decline in eelgrass habitat in the system.

Other factors which influence eelgrass bed loss in embayments may also be at play in the Menemsha Pond Portion of the estuary. While the general loss seems completely in-line with slight nitrogen enrichment, and is consistent with the sediment conditions and benthic communities (see below), localized losses within the Pond from other factors need to be considered. Therefore, 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 main basin does not support a high density of boat moorings in the areas where eelgrass habitat is prevalent as well as in areas where loss has occurred. Similarly, pier construction (virtually non-existent) and boating pressure may be adding additional stress but seem to be relatively minor factors in the overall system. However, stress associated with boating activities and shell fishing cannot be completely ruled out as a contributing factor. On the other hand, dredging of the main channel either directly or indirectly causes shifts in eelgrass coverages. Indirect effects are typically associated with maintenance of high velocity flows which cause unstable surface sediments, development of sand bars or shifting sands. However in most cases these areas also have very high water quality and water clarity as they tend to be associated tidal inlet channels. To the extent that eelgrass coverage is changing in the Menemsha Creek/Channel it is almost certainly due to these factors and is not related to nitrogen enrichment.

Based on the available data from the 1995-2006 surveys, it is possible to estimate the extent to which eelgrass beds might be recovered if nitrogen management alternatives were implemented (Figure VII-19). This determination is based upon the MassDEP Mapping Program and would indicate that the existing eelgrass coverage could be conservatively enhanced by ~25% within the Menemsha Pond portion of the overall system with nitrogen remediation (Table VII-3).

The relative pattern of habitat quality in Menemsha Pond based upon the eelgrass data is consistent with the results of the oxygen and total pigment time-series data (Section VII.2), nitrogen levels within the main basin and tributary basins (Section VI) and the benthic infauna analysis (Section VII.4). The absence of eelgrass beds from Squibnocket Pond is supported by the low salinity data, the structure of the basin, high nitrogen levels, and the low water clarity. It is not likely that this portion of the overall system ever supported eelgrass. Overall, it appears that the Menemsha/Squibnocket Pond Embayment System has slightly exceeded its assimilative capacity for nitrogen with the resulting recent gradual decline in eelgrass coverage in the Menemsha Pond portion of the system, while generally maintaining high quality habitat in the open water main basin.

Table VII-3. Change in eelgrass coverage within the Menemsha / Squibnocket Pond Estuarine System, Towns of Chilmark, Aquinnah and the Wampanoag Tribe of Aquinnah, as determined by the MassDEP Eelgrass Mapping Program (C. Costello).

Menemsha Pond - Eelgrass	1951	1995	2001	2006	Percent Difference 1995-2006
Acres	406.41	427.10	371.60	319.44	25%
Note: Data developed by MassDEP Eelgrass Mapping Program (C. Costello)					

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling for benthic community characterization was conducted at 29 locations throughout the Menemsha-Squibnocket Pond Embayment System (Figure VII-20). Sampling sites were located in the brackish water basin of Squibnocket Pond (11) and the marine basins of Menemsha Pond (13), Nashaquitsa Pond (3) and Stonewall Pond (2). At each site multiple assays were conducted. In all areas and particularly those that do not support eelgrass beds (e.g. Squibnocket Pond), 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 historical absence of eelgrass beds in Squibnocket Pond, nitrogen enrichment in that portion of the overall embayment system is being evaluated relative to the characteristics of the benthic animal community and the other water quality and ecological metrics (see Table VIII-1). By contrast, given the extensive presence of eelgrass historically throughout the 4 regions of the Menemsha Pond Embayment, nitrogen enrichment in that portion of the system is being evaluated relative to both eelgrass distribution and benthic animal community characteristics. The benthic infauna analysis is important for determining the level of impairment (healthy→moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Section VIII).

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

Figure VII-20. Aerial photograph of the Menemsha- Squibnocket Pond Embayment System showing location of benthic infaunal sampling stations (green symbols). MEN-12,13 are located in Stonewall Pond and MEN-14,15,16 are located in Nashaquitsa Pond.

Overall, the infauna survey indicated that some of the sub-basins comprising the Menemsha-Squibnocket Pond Embayment System are presently beyond their ability to tolerate additional nitrogen inputs without impairment. Consistent with the observed periodic oxygen depletions and occasional large phytoplankton blooms occurring in the main depositional basins, and areas of macroalgal accumulation and algal mats, in these areas the benthic animal communities are showing moderate impairment. However, in the main basin of Menemsha Pond and Menemsha Creek, oxygen and organic matter loading is low, sediments are oxidized and there are no significant macroalgal accumulations. These areas are currently supporting high quality benthic animal habitat. The impaired areas are consistent with organic enrichment resulting from nitrogen enrichment, from a combination of watershed inputs. In Squibnocket Pond, nitrogen inputs are magnified by the low tidal flushed through the herring run, which appears to dominate the habitat quality.

The Benthic Survey of the Menemsha-Squibnocket Pond Embayment System did not reveal any areas of severe degradation (less than 70 animal per grab), or very low numbers of species (4-5) or dominance by opportunistic stress indicator species such as Capitellids and Tubificids. In fact, all of the system's sub-basins supported high numbers of individuals (400-1400 per grab sample) and low numbers of opportunistic stress indicator species (Capitellids and Tubificids, generally <10% of community). Community metrics of diversity (H') and Evenness (E) paralleled the nutrient metrics (oxygen, chlorophyll, macroalgae, and TN) indicating highest quality areas in Menemsha Creek and Menemsha main basins (H'>3.0; E >0.7) with declining quality moving from Nashaquitsa Pond (H'=2.6; E=0.6) and Stonewall Pond (H'=2.2; E=0.6), both with moderate impairment, and lowest habitat quality in Squibnocket Pond (H'>1.7; E 0.55). However, all areas currently support productive benthic habitat based on numbers of organisms present and the low fraction of stress indicator organisms in the communities (Table VII-4). Species numbers of 20-25 and diversity >3.0 generally indicate high quality benthic habitats. While there is little evidence of high levels of nitrogen related impairment of the benthic animal communities, the enclosed sub-basins did show clear evidence of moderate to significant impairment associated with nitrogen and organic matter enrichment.

The benthic animal communities within the Menemsha-Squibnocket Pond Embayment System were compared to highest quality environments in the MEP region, such as the Outer Basin of Quissett Harbor and Lewis Bay. The Outer Basin of Quissett Harbor supports benthic animal communities with ≥28 species, >400 individuals with high diversity (H' ≥3.7) and Evenness (E ≥0.77). Similarly, outer stations within Lewis Bay in Barnstable currently support similarly very high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Eveness (0.74). Equally important these communities are not consistent with nutrient enrichment being composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms.

Specifically, Menemsha Creek is showing very high habitat quality for benthic animals averaging 25 species and 1500 individuals per grab with high diversity (H'=3.35) and Evenness (E=0.73) and only 12% tubificids and capitellids. Similarly, the main basin of Menemsha Pond is currently supporting high habitat quality for benthic animals averaging 20 species and 600 individuals per grab with high diversity (H'=3.12) and Evenness (E=0.73) and <20% tubificids and capitellids. The benthic animal communities of both sub-basins are dominated by crustacean, polychaetes and crustaceans, with some stress tolerant small opportunistic species (<20% tubificids and capitellids). There is a pattern in Menemsha Pond where the highest quality habitat is in the shallow areas not in the deep southern basin. This is typical, as the deep basin is depositional and there is some organic enrichment of the sediments, although not sufficient to impair the benthic animal habitat there is some impairment of eelgrass habitat.

Table VII-4. Benthic infaunal community data for the Menemsha Pond and Squibnocket Pond Embayment System. Squibnocket Pond is connected to Menemsha Pond by a herring run and has significantly reduced tidal characteristics compared to Menemsha Pond and its tributary basins (Nashaquitsa/Stonewall Ponds). Estimates of the number of species adjusted to the number of individuals and diversity (H') and evenness (E) of the community allow comparison between locations. Samples represent surface area of 0.0625 m^2. Stations refer to map in Figure VII-20, replicate samples were collected at each location.

Sub-Embayment	Station ID	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Menemsha Pond						
Menemsha Creek	MEN 1,5,21	**25**	**1566**	**15**	**3.35**	**0.73**
Menemsha Main Basin	MEN 7,9,10,18,19,22-24	**20**	**609**	**15**	**3.12**	**0.73**
Nashaquitsa Pond	MEN 14,15,16	**17**	**871**	**11**	**2.56**	**0.63**
Stonewall Pond	MEN 12, 13	**14**	**1444**	**9**	**2.19**	**0.57**
Squibnocket Pond						
Squibnocket Main Basin	SQB 1-8,10,13,15,16	**9**	**430**	**6**	**1.72**	**0.55**

The enclosed basins of Nashaquitsa Pond and Stonewall Pond are showing a moderate level of impairment to benthic animal habitat. Although they maintain productive benthic animal communities (high numbers of organisms, >800 per grab), they have only moderate numbers of species (14-17), diversity (H' 2.6-2.2) and Evenness (0.57-0.63). Consistent with moderate organic matter enrichment, this area is a community dominated by amphipods with mainly polychaetes.

Squibnocket Pond with its restricted tidal flows is nitrogen enriched (mainly from poor flushing) and brackish. Squibnocket Pond is currently supporting a slightly higher level of impairment than Nashaquitsa and Stonewall Pond although it still supports a productive benthic animal community (moderate to high numbers of organisms, >400 per grab). However, there are fewer species (9) and lower diversity (H' 1.72) and Evenness (0.55). These metrics are consistent with the measured oxygen, chlorophyll, macroalgal accumulations and organic enrichment of the sediments. The basin's benthic animal community is generally dominated by *Streblospio* and *Leptocheirus* (amphipod), with few stress indicator species.

For the purposes of comparison, the benthic animal community metrics from the nearby basins of Lower Chilmark Pond (east), Wades Cove and Gilberts Cove in the Chilmark Pond Estuary were examined. These basins are showing moderate-significant levels of impairment at similar chlorophyll-*a* levels and moderate periodic oxygen depletions. In these basins the numbers of individuals are also relatively high but the numbers of species and their diversity and evenness are moderate and indicative of a community under moderate ecological stress. In all cases, these basins support communities with diversities of only 1.45 to 2.21. Very similar to impaired benthic communities in the tributary coves to nearby Tisbury Great Pond, 1.44 to 1.82. Evenness (how individuals are distributed among the species) was similarly low, in Chilmark Pond, 0.54-0.66 and indicated that only a few species were accounting for most of the individuals within each basin. There was little substantive difference between the basins as all are clearly moderately impaired relative to benthic animal habitat. As another point of comparison, the moderately impaired lower basins of Tisbury Great Pond had similar diversity indices of 2.0 to 2.3 and evenness of 0.49 to 0.54. In addition, benthic communities in Chilmark Pond's estuarine basins were dominated by non-opportunistic stress indicators (generally >90%), but are tolerant of moderate levels of organic enrichment (*Streblospio* and amphipods). *Streblospio* was a dominant species within the coves tributary to Tisbury Great Pond as well.

Given the prevalence of species tolerant of moderate organic enrichment (*Streblospio* and amphipods: *Ampelisca* and *Leptocheirus*), the low numbers of stress indicator organisms, the moderate numbers of species with high numbers of individuals, the moderate diversity and Evenness of the 3 enclosed basins to Menemsha Pond, benthic communities compared to high quality habitat areas in similarly structured embayments in southeastern Massachusetts. It is clear that Nashaquitsa, Stonewall and Squibnocket basins are currently above their nitrogen threshold and are supporting moderately impaired benthic animal habitat.

The results of the infauna survey and complete absence of eelgrass coverage within the Squibnocket Pond Embayment System indicates that the nitrogen management threshold analysis (Section VIII) needs to aim for lowering nitrogen enrichment for restoration of infaunal habitat in this basin. In contrast, the impairment of benthic animal habitat and loss of eelgrass from the Nashaquitsa and Stonewall Pond basins indicates that nitrogen management needs to focus on lowering TN levels, mainly to restore eelgrass habitat. Restoration of eelgrass habitat in these 2 basins will also result in the restoration of benthic animal habitat as eelgrass is more sensitive to nitrogen enrichment and therefore requires a greater reduction in nitrogen than the associated benthic animal habitat. In these 3 major component basins of the Menemsha-Squibnocket Embayment System, reduction in nitrogen enrichment is required for restoration. It should be emphasized that reducing nitrogen enrichment can be achieved by reducing nitrogen inputs and/or increasing the rate of nitrogen loss through enhanced tidal exchange. Restoring these nitrogen impaired habitats in these 3 basins will also provide protection/restoration of eelgrass habitat in Menemsha Pond (Section VIII).

Other Biological Resources:

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth 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 (Figures VII-21,VII-22,VII-23). As is the case with some systems on Cape Cod, the enclosed waters of Menemsha Pond and most of Squibnocket Pond are open for the taking of shellfish year round. This generally open status Menemsha Pond and large portion of Squibnocket Pond is potentially due to the good habitat quality. The eastern portion of Squibnocket Pond that is classified as prohibited to shell fishing is most likely due to bacterial contamination from wildlife in an area where there are significant wetland surfaces surrounding that part of the Pond. The major shellfish species with potential habitat within the Menemsha, Nashaquitsa and Stonewall Pond Estuary are mainly Quahog (*mercenaria*) and soft shelled clams (*Mya arenaria*) and Squibnocket Pond supports habitat mostly suited to the American Oyster (Figures VII-24,VII-25). The habitat in Squibnocket Pond designated as suitable for oysters, may present an opportunity for some nitrogen mitigation through oyster propagation.

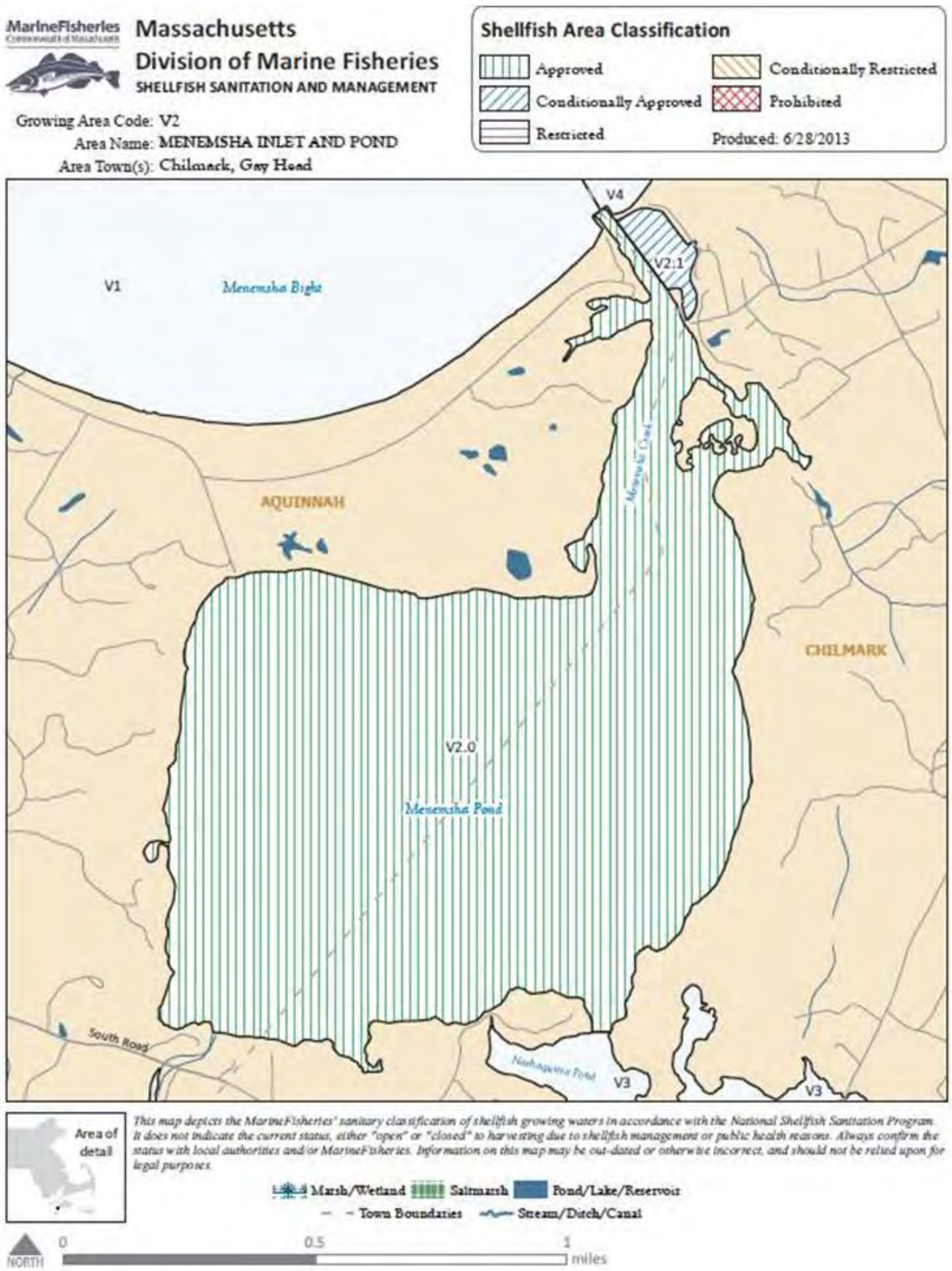

Figure VII-21. Location of shellfish growing areas and their status relative to shellfish harvesting in Menemsha Pond as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas. However, areas dominated by wetlands with persistent fecal coliform levels >14 cfu per 100 mL may be prohibited to shellfishing until the cause of the contamination (frequently wildlife and birds) is documented.

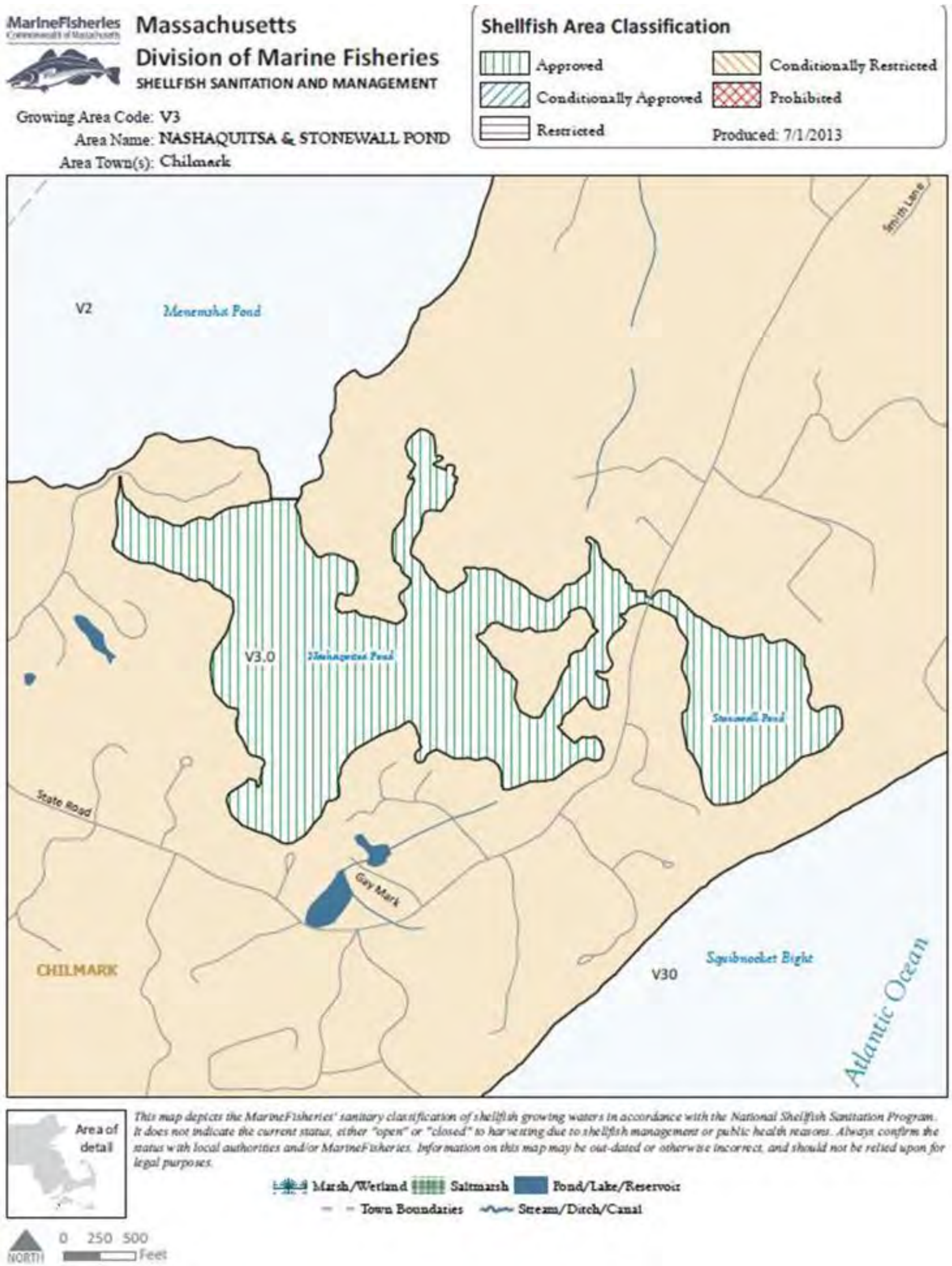

Figure VII-22. Location of shellfish growing areas and their status relative to shellfish harvesting in Nashaquitsa Pond and Stonewall Pond as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas. However, areas dominated by wetlands with persistent fecal coliform levels >14 cfu per 100 mL may be prohibited to shellfishing until the cause of the contamination (frequently wildlife and birds) is documented.

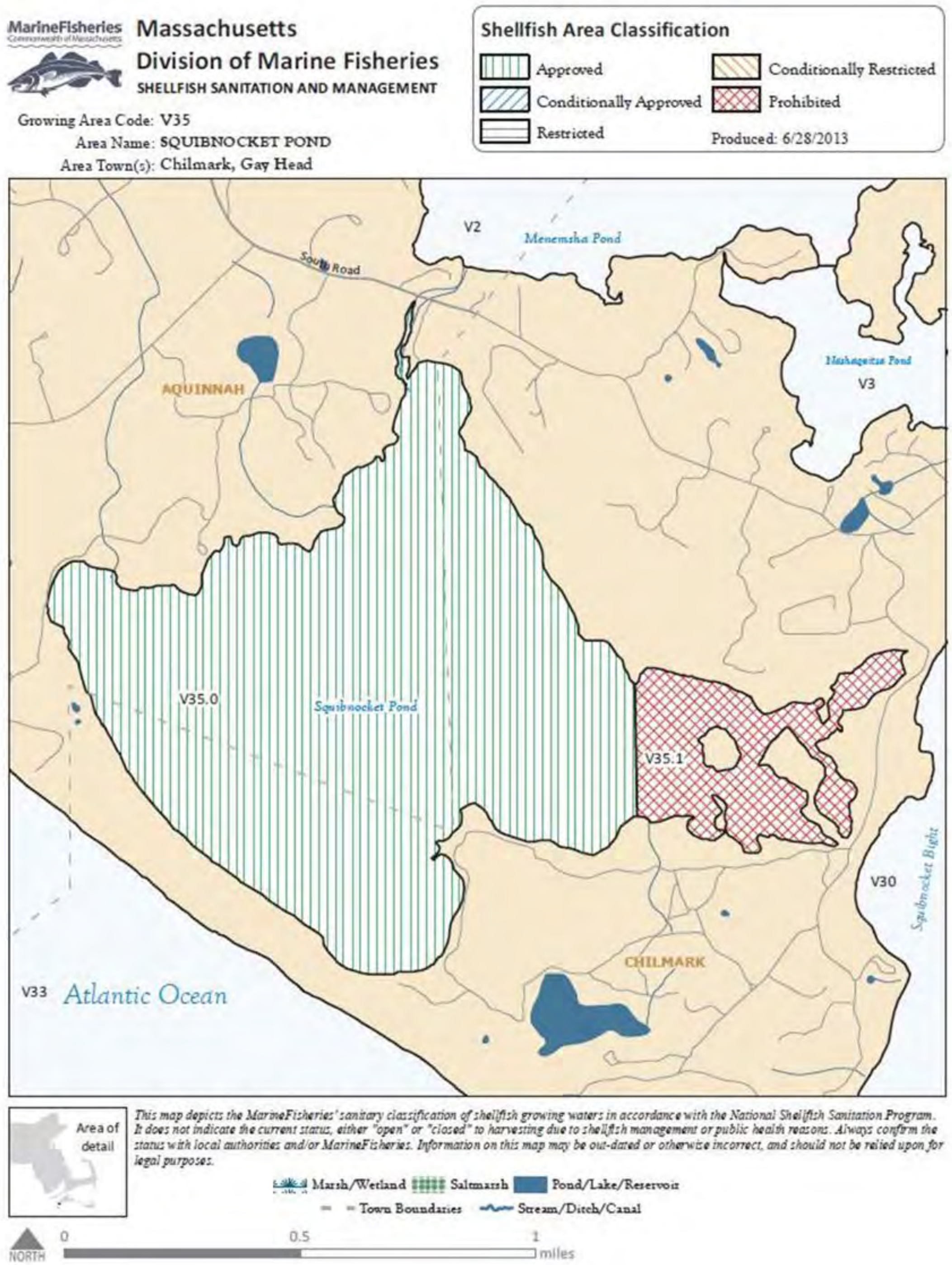

Figure VII-23. Location of shellfish growing areas and their status relative to shellfish harvesting in Squibnocket Pond as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas. However, areas dominated by wetlands with persistent fecal coliform levels >14 cfu per 100 mL may be prohibited to shellfishing until the cause of the contamination (frequently wildlife and birds) is documented.

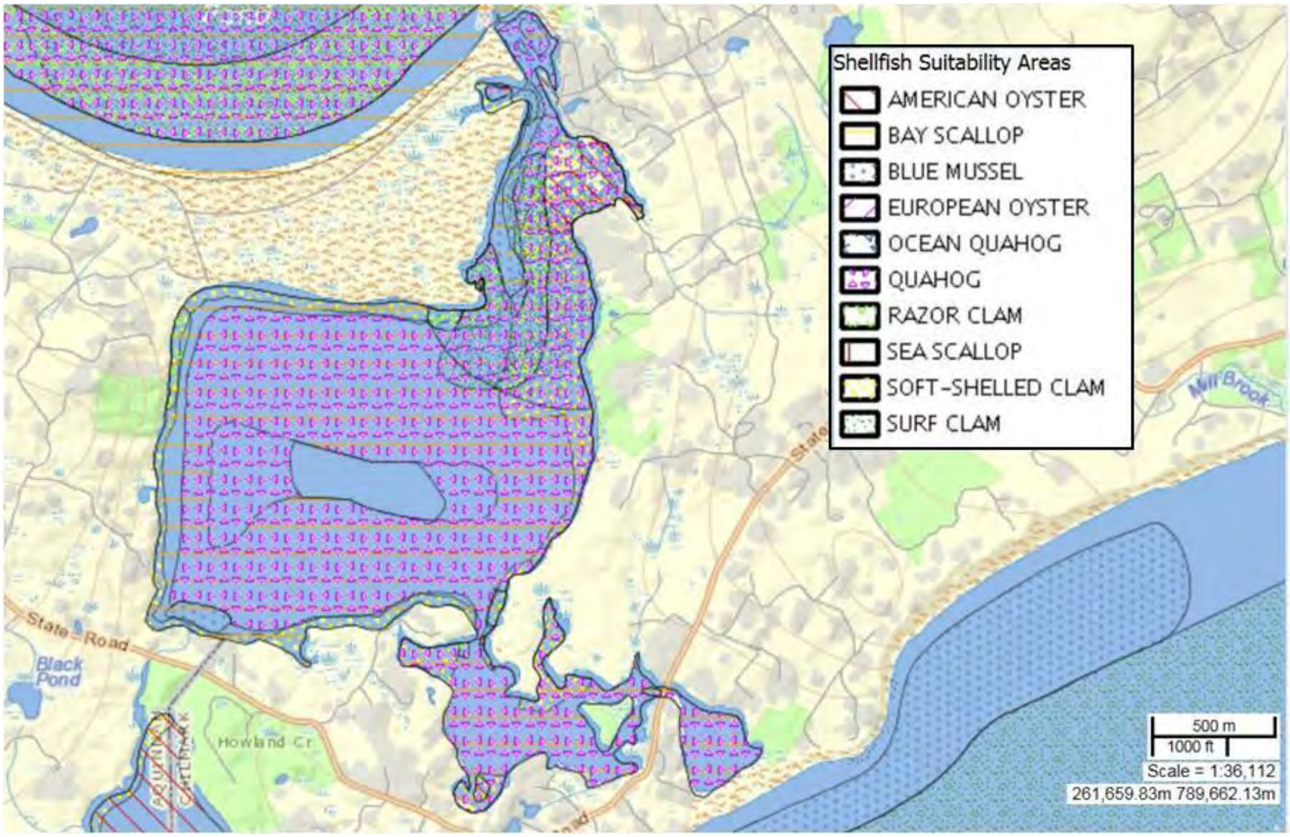

Figure VII-24. Location of shellfish suitability areas within the Menemsha Pond sub-embayment as determined by Mass. Division of Marine Fisheries. Suitability does not necessarily mean that a shellfish population is "present" or that harvest is allowed.

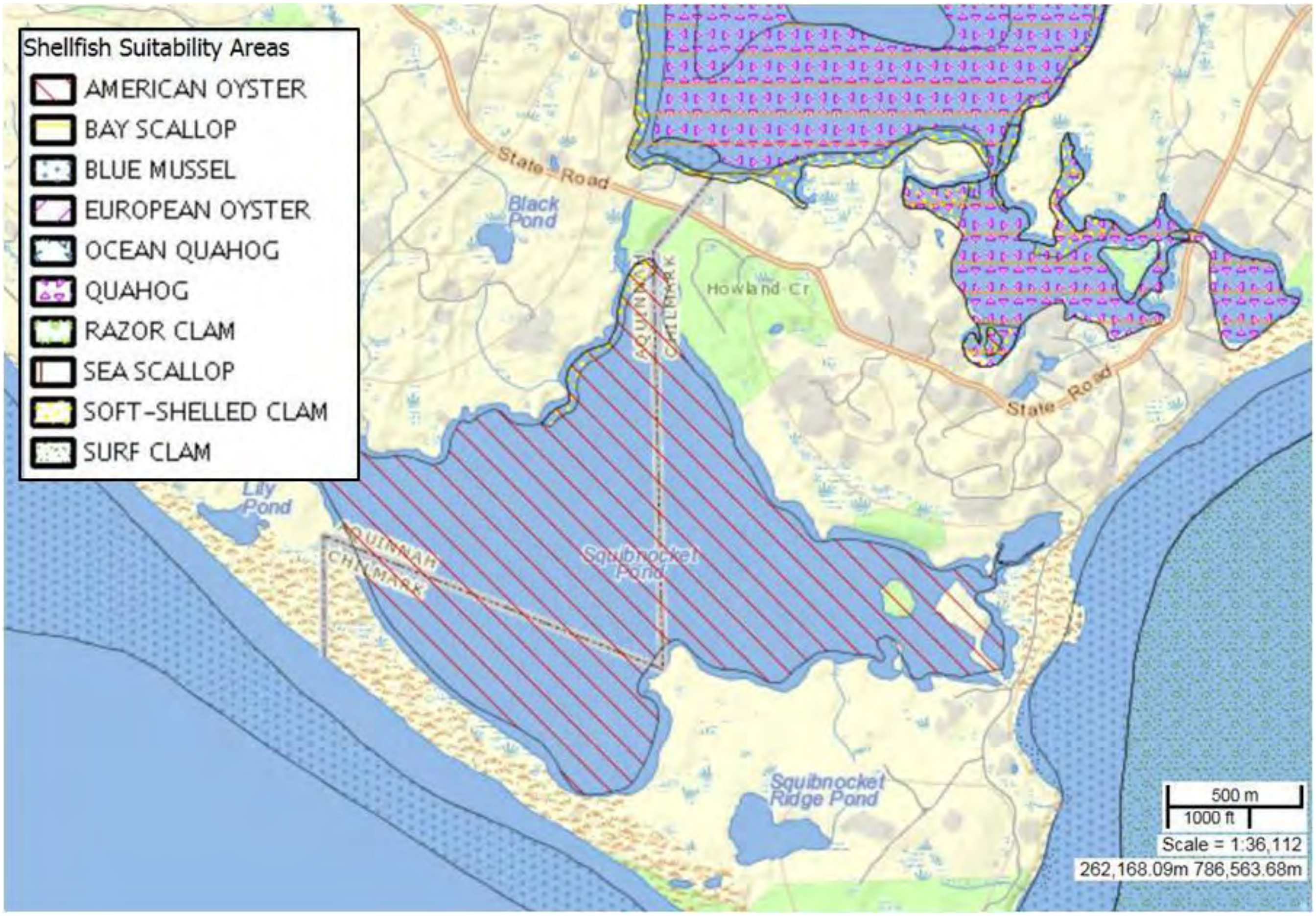

Figure VII-25. Location of shellfish suitability areas within the Squibnocket Pond sub-embayment as determined by Mass. Division of Marine Fisheries. Suitability does not necessarily mean that a shellfish population is "present" or that harvest is allowed. The habitat in Squibnocket Pond designated as suitable for oysters, may present an opportunity for some nitrogen mitigation through oyster propagation.

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 Menemsha-Squibnocket Pond Embayment System by the MEP and were discussed in Section VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the water quality model (Chapter VI) based upon the baseline Water Quality Monitoring Program (MVC, Wampanoag Tribe, Towns of Chilmark & Aquinnah) with analytical support from the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

The Menemsha-Squibnocket Pond Embayment System is a complex estuary created by rising sea-level entering the large basin of Menemsha Pond and associated sub-basins. Squibnocket Pond appears to have been a separate salt pond that has been connected via a herring run to the main basin of Menemsha Pond. At present the tidal connection between these 2 large basins is insufficiently sized to support high quality habitat within Squibnocket Pond as seen by its low watershed N loading, yet high TN and low salinity. Menemsha-Squibnocket Pond Embayment System consists of a large tidal marine basin with tidal channel (Menemsha Creek, Menemsha Pond) and 2 sub-basins (Nashaquitsa Pond and Stonewall Pond). In addition, Squibnocket Pond exchanges tidal waters with the main basin of Menemsha Pond. All component basins are currently functioning as typical coastal embayment basins with boundary waters entering from Vineyard Sound. Each type of functional component to an estuary (salt marsh basin, embayment, tidal river, deep basin {sometimes drowned kettles}, shallow basin, etc.) has 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 basin and its ability to support eelgrass beds and infaunal communities. At present, Menemsha Pond, Nashaquitsa Pond and Stonewall Pond are just beyond their ability to assimilate nitrogen without impairment and are showing a low level of nitrogen enrichment, with moderate impairment of eelgrass in Menemsha Pond and Nashaquitsa Pond and significant impairment of eelgrass in Stonewall Pond (due to recent complete loss of coverage). Direct observations in 1995 by MassDEP showed eelgrass throughout each of these 3 basins. It also appears that Nashaquitsa, Stonewall and Squibnocket Pond have exceeded their nitrogen loading limit relative to sustaining high quality infaunal habitats (Table VIII-1). The biologic criteria for measuring impairment are indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

The level of oxygen depletion and the magnitude of daily oxygen excursion and total pigment levels as a measure of phytoplankton biomass indicate low to moderate nutrient enriched waters throughout Nashaquitsa, Stonewall and Squibnocket basins. (Figures VII-3 through VII-18). Overall, the observed levels of oxygen depletion were consistent with a moderate level of organic matter enrichment, with greatest enrichment in Squibnocket Pond, primarily from phytoplankton production, macroalgae and microalgal mats. The measured levels of oxygen

Table VIII-1. Summary of nutrient related habitat quality within the Menemsha-Squibnocket Embayment System within the Towns of Chilmark and Aquinnah, MA, based upon assessments in Section VII. WQMP indicates Water Quality Monitoring Program.

Health Indicator	Menemsha-Squibnocket Embayment System				
	Menemsha Channel	Menemsha Main Basin	Nashaquitsa Pond	Stonewall Pond	Squibnocket Pond
Dissolved Oxygen	H[1]	HI[1]	HI[1]	MI[2]	MI/SI[3]
Chlorophyll	H[4]	H/MI[5]	MI[6]	MI/SI[7]	H/MI[5]
Macroalgae	H[8]	H/MI[9]	H[8]	H[8]	H/MI[10]
Eelgrass	H[11]	H/M[11]	SI[12]	SI[12]	--[13]
Infaunal Animals	H[14]	H[15]	MI[16]	MI[16]	MI[17]
Overall:	**H[18]**	**H/MI[19]**	**MI/SI[20]**	**SI[21]**	**MI[22]**

1- oxygen always >4mg/L and above 5 mg/L 91%-96% of record and for Nashaquitsa >6 mg/L for 97% of record.
2- moderate to high oxygen depletion, <6mg/L 36%, <4 mg/L 5% of record and periodically <2 mg/L
3- except for near the channel to Menemsha Pond, oxygen has high diurnal shifts (6-12 mg/L), frequent depletion to <4 mg/L, 8%-26% of record and <3mg/L 4%-16% of record, with declines to <2mg/L common, with some anoxia.
4- levels low for a coastal basin, averaging 7 ug/L over summer time series generally between 5-10 ug/L, >90% of the time <10 ug L^{-1} and always <15 ug L^{-1}..
5 - low to moderate for a coastal basin, 6-8 ug/L, >10 ug/L ~24% of record and rarely >15ug/L.
6- moderate for a coastal basin, averaging 8.4 ug/L, but >10 ug/L 18% of record with blooms to 25 ug/L.
7- moderate to high for a coastal basin averaging 10 ug/L, >20 ug/L 8% of record with periodic blooms to >25 ug/L
8- sparse to no macroalgae throughout this basin.
9- modest accumulations of green filamentous drift algae accumulating in shallow area of mid basin, but generally absent.
10- sparse to no macroalgae in North region, but south region has relatively high accumulation and east region dense micro-algal mat covering sediments.
11- most of the main basin margin supports eelgrass habitat, loss of some deeper beds and fringing beds throughout basin. No clear loss of beds associated with N enrichment in Channel. Temporal/spatial loss pattern of loss in Main Basin is typical of nitrogen enrichment (loss deeper, stable in shallows) and indicates moderate impairment.
12- basin coverage in 1995 completely lost in Stonewall; Nashaquitsa loss from deep area, now shrinking of fringing beds.
13- no documented (verified) evidence of eelgrass "presence" in this basin historically.
14 - very high habitat quality, averaging 25 species & 1500 individuals per grab with high diversity (H'=3.35) and Evenness (E=0.73) and community 90% non-stress indicator species with crustaceans and mollusks and polychaetes dominant.
15 – high habitat quality averaging 20 species and 600 individuals per grab with high diversity (H'=3.12) and Evenness (E=0.73) and <20% tubificids and capitellids. Communities dominated by crustacean, polychaetes and crustaceans. Main basin has highest quality habitat is in the shallow areas not in the deep southern depositional basin
16-productive benthic animal communities (high numbers of organisms, >800 per grab), but only moderate numbers of species (14-17), diversity (H' 2.6-2.2) and Evenness (0.57-0.63). Consistent with moderate organic matter enrichment is a community dominated by amphipods with mainly polychaetes colonizing soft organic muds.
17- slightly higher impairment than Nashaquitsa and Stonewall Ponds, but supports a productive community (moderate to high numbers of organisms, >400 per grab) with fewer species (9) and lower diversity (H' 1.72) and Evenness (0.55), community is generally dominated by *Streblospio* and *Leptocheirus* (amphipod), with few stress indicator species..
18 High water quality, diversity productive benthic community, no macroalgae, oxidized sediments and stable eelgrass.
19 - High water quality, diversity productive benthic community, no macroalgae, oxidized sediments. Generally stable eelgrass coverage with only slight indication of loss in deeper waters of deep southern basin, the slight loss of eelgrass requires a designation moderately impaired, although benthic animal habitat remains of high quality..
20 – moderate oxygen depletion and elevation chlorophyll with organic soft sediments. Significant loss of eelgrass coverage since 1995 some remaining. Overall, moderately to significantly impaired eelgrass habitat and moderately impaired benthic animal habitat.
21- as for #20 above, except that eelgrass loss is complete gaining a designation significantly impaired for eelgrass.
22 - no eelgrass habitat historically. Supports productive but moderately impaired benthic infauna habitat with low to moderate species, diversity and Evenness. Moderate impairment is consistent with the levels of oxygen depletion, macroalgal accumulations and mats, organic rich soft sediments in much of the basin and high nitrogen levels. As found in many moderately impaired benthic habitats, the community is dominated by *Leptocheirus* (amphipod) and *Streblospio*

H = High quality habitat conditions; MI = Moderate Impairment; SI = Significant Impairment;
SD = Severely Degraded; -- = not applicable to this estuarine reach

depletion and enhanced chlorophyll-*a* levels at specific locations in the embayment system are consistent with the nitrogen levels within the various basins (Section VI), and the parallel variation in these water quality parameters is consistent with the balance of watershed based nitrogen enrichment and flushing of each of the component sub-embayment basins.

The oxygen records show that the innermost sub-embayment of Menemsha Pond, specifically the Stonewall Pond tributary of Nashaquitsa Pond, which collectively receives significant watershed nitrogen loading relative to tidal flushing rates, has the largest daily oxygen excursions (a nutrient related response). Similarly, the innermost mooring locations (Squibnocket-south, east, west) in the Squibnocket Pond basin also showed large oxygen excursions. This is a response to the organic rich characteristics of the basin sediments and poor circulation and exchange with Menemsha Pond. Only the northern region showed relatively low oxygen excursion and depletion, with relatively low chlorophyll a levels, likely associated with its proximity to the tidal channel (herring run) which carries the tidal exchange between Squibnocket Pond and the relatively low nitrogen waters of Menemsha Pond main basin.

Measured dissolved oxygen depletion indicates that portions of the Menemsha-Squibnocket Pond Embayment System, specifically Stonewall Pond and Squibnocket Pond are moderately impaired. The largest oxygen depletions and excursions were observed in Squibnocket Pond, particularly in the more poorly flushed areas farther from the herring run. The oxygen record obtained from the western sector of Squibnocket Pond showed significant oxygen depletion particularly in the beginning of the deployment period, with oxygen stress decreasing over the course of the deployment. The main basin of Menemsha Pond did not show signs of oxygen stress, however, the tributary basin farthest from the tidal inlet, Stonewall Pond, showed large oxygen depletions similar to what was observed at the Squibnocket Pond-south and east mooring locations. It appears that the sites that are furthest away from an inlet with reduced access to low nitrogen waters also have the greatest oxygen stress. These areas are also depositional environments with sediments that are high in organic content. The observed spatial pattern indicated that the level of oxygen depletion (Table VII-1a,b) and chlorophyll-*a* (Table VII-2a,b) and total nitrogen levels increased with increasing distance from the tidal inlet to Menemsha Pond as well as increasing distance from the culvert connecting Menemsha Pond to Squibnocket Pond. Squibnocket Pond with its highly restricted tidal exchange also supports much higher nitrogen levels than the rest of this embayment system. Given its structure, the conditions in Squibnocket Pond appear to be mainly related to its very low flushing which appears to explain the historic lack of eelgrass coverage in this basin. Improving the exchange between Stonewall Pond and Nashaquitsa Pond to Menemsha Pond as well as the exchange between Squibnocket Pond and Menemsha Pond (or periodic breach of Squibnocket Pond through the barrier beach to directly exchange pond waters with low nitrogen offshore waters likely provides the only mechanism to sufficiently lower nitrogen levels (and associated negative effects) to improve benthic animal habitat throughout this basin.

The measured levels of oxygen depletion and total pigment (chlorophyll-a + pheophytin) levels follows the spatial pattern of total nitrogen levels in this system (Section 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 organic matter enrichment of sediments, enhancement of total pigment levels and total nitrogen concentrations increased from the offshore waters to Stonewall Pond and Squibnocket Pond, where nitrogen was highest of all component basins. The pattern of oxygen depletion, elevated chlorophyll-*a* and nitrogen levels are consistent with the present distribution and level of eelgrass loss (Section VII.3) and regions with benthic animal habitats (Section VII.4) within the Menemsha-Squibnocket Pond Embayment System. These assessments indicate an estuarine system that is beyond its ability to assimilate nitrogen loads without impairment.

All of the available information on eelgrass within the Menemsha Creek/Channel, Menemsha Pond, Nashaquitsa Pond and Stonewall Pond portions of the estuarine system indicates that these basins supported large system-wide eelgrass coverage as recently as 1995. However, although the system continues to support significant eelgrass beds, there has been a clear decline in acreage over the past 20 years. The absence of significant eelgrass habitat within Squibnocket Pond is consistent with its structure, tidal flushing and brackish waters and indicates that benthic infauna habitat is the focal resource for assessment of impairment by nitrogen enrichment in that basin, while eelgrass habitat should be the focus within Menemsha-Nashaquitsa-Stonewall Pond basins.

Temporal changes in eelgrass distribution show stable beds and coverage within Menemsha Creek and Channel as is expected given its proximity to the system's inlet where high quality low nitrogen waters are exchanged with the Atlantic Ocean twice a day. Within the main basin of Menemsha Pond, the 1995-2006 surveys show a slight loss from the deeper waters of the deep basin (southern portion) and relatively stable fringing beds colonizing the shallow margins of the deep basin and the shallow northern half of the main basin. In contrast, Nashaquitsa Pond and Stonewall Pond show significant losses in eelgrass coverage, with complete loss in Stonewall Pond (by 2006) and a near complete loss in Nashaquitsa Pond. Eelgrass decline in the Nashaquitsa basin (since 1995) follows the pattern diagnostic of nitrogen enrichment. The initial loss was from the deeper waters in the central basin first leaving only fringing beds, then a narrowing of the fringing beds and loss entirely from the inner reach. At present only narrow fringing beds occur in the 1/3 of the Nashaquitsa Basin nearest its opening to the main basin of Menemsha Pond which is its highest flushed region. Sediments in these 2 smaller basins are mainly soft muds with only a thin oxidized surface and in some cases fluid sulfidic muds, consistent with organic matter enrichment. As noted below the benthic infauna in these basins is also consistent with a transitional environment due to organic matter enrichment. In contrast the sediments in eelgrass areas of Menemsha Pond and Channel are medium to coarse sands with an oxidized surface layer and even the deep basin of Menemsha Pond with fine grained consolidated sediments presenting an oxidized surface.

The observed pattern of loss of eelgrass coverage from deeper water areas to shallower water areas is typical of loss resulting from nitrogen enrichment through increased turbidity and decreased light penetration as summer phytoplankton biomass increases. Average total pigment levels are moderate to high, 8.4 ug L^{-1} and 10.0 ug L^{-1} in Nashaquitsa Pond and Stonewall Pond, respectively, the water is sufficiently deep (2.5 – 3.0 m) for this to limit light penetration to the bottom, restricting eelgrass habitat to the shallow areas. The loss of eelgrass appears to result mainly from decreased light penetration (from increased phytoplankton and epiphytes on eelgrass) as significant macroalgal accumulations were not observed in any basin within the Menemsha-Squibnocket Pond Embayment System. While the Menemsha-Squibnocket Pond Embayment System does support some of the highest quality eelgrass habitat associated with its generally highest water quality among southeastern Massachusetts Estuaries, the recent apparent gradual decline in eelgrass habitat in the inner basins tributary to Menemsha Pond and slight decline in Menemsha Pond's deep basin indicates that this system is just beyond its threshold level of nitrogen enrichment. As such, further increases in nitrogen loading will almost certainly drive additional significant decline in eelgrass habitat in the system.

The relative pattern of eelgrass habitat quality in Menemsha Pond is consistent with the results of the oxygen and total pigment time-series data (Section VII.2), nitrogen levels within the main basin and tributary basins (Section VI) and the benthic infauna analysis (Section VII.4). The absence of eelgrass beds from Squibnocket Pond is supported by the low salinity data, the structure of the basin, high nitrogen levels, and the low water clarity. It is not likely that this portion of the overall system ever supported eelgrass. Overall, it appears that the

Menemsha/Squibnocket Pond Embayment System has slightly exceeded its assimilative capacity for nitrogen with the resulting recent gradual decline in eelgrass coverage in the Menemsha Pond portion of the system, while generally maintaining high quality habitat in the open water main basin.

Overall, the infauna survey indicated that some of the sub-basins comprising the Menemsha-Squibnocket Pond Embayment System are presently beyond their ability to tolerate additional nitrogen inputs without impairment. Consistent with the observed periodic oxygen depletions and occasional large phytoplankton blooms occurring in the main depositional basins, and areas of macroalgal accumulation and algal mats, in these areas the benthic animal communities are showing moderate impairment. However, in the main basin of Menemsha Pond and Menemsha Creek, oxygen and organic matter loading is low, sediments are oxidized and there are no significant macroalgal accumulations. These areas are currently supporting high quality benthic animal habitat. In contrast, the impaired areas in Nashaquitsa, Stonewall and Squibnocket Ponds are consistent with organic enrichment resulting from nitrogen enrichment. In Squibnocket Pond, nitrogen inputs are magnified by the low tidal flushing through the herring run, which appears to dominate the habitat quality.

The benthic survey of the Menemsha-Squibnocket Pond Embayment System did not reveal any areas of severe degradation (less than 70 animals per grab), or very low numbers of species (4-5) or dominance by opportunistic stress indicator species such as Capitellids and Tubificids. In fact, all of the system's sub-basins supported high numbers of individuals (400-1400 per grab sample), low numbers of opportunistic stress indicator species (Capitellids and Tubificids, generally <10% of community). Community metrics of diversity (H') and Evenness (E) paralleled the nutrient metrics (oxygen, chlorophyll, macroalgae, and TN). These metrics indicated highest quality areas in Menemsha Creek and Menemsha main basins (H'>3.0; E >0.7), with declining quality moving from Nashaquitsa Pond (H'=2.6; E=0.6) to Stonewall Pond (H'=2.2; E=0.6), both with moderate impairment (lowest habitat quality being in Squibnocket Pond {H'>1.7; E 0.55}). However, all areas currently support productive benthic habitat based on numbers of organisms present and the low fraction of stress indicator organisms in the communities (Table VII-4). Species numbers of 20-25 and diversity >3.0 generally indicate high quality benthic habitats. While there is little evidence of high levels of nitrogen related impairment of the benthic animal communities, the enclosed sub-basins did show clear evidence of moderate to significant impairment associated with nitrogen and organic matter enrichment as manifested in the DO records of moorings deployed furthest from the inlets to each component of the system.

The results of the infauna survey and complete absence of eelgrass coverage within the Squibnocket Pond Embayment System indicates that the nitrogen management threshold analysis (Section VIII) needs to aim for lowering nitrogen enrichment for restoration of infaunal habitat in this basin. In contrast, the impairment of benthic animal habitat and loss of eelgrass from the Nashaquitsa and Stonewall Pond basins indicates that nitrogen management needs to focus on lowering TN levels, mainly to restore eelgrass habitat. Restoration of eelgrass habitat in these 2 basins will also result in the restoration of benthic animal habitat as eelgrass is more sensitive to nitrogen enrichment and therefore requires a greater reduction in nitrogen than the associated benthic animal habitat. In these 3 major component basins of the Menemsha-Squibnocket Embayment System, reduction in nitrogen enrichment is required for restoration. It should be emphasized that reducing nitrogen enrichment can be achieved by reducing nitrogen inputs and/or increasing the rate of nitrogen loss through enhanced tidal exchange. Restoring these nitrogen impaired habitats in these 3 basins will also provide protection/restoration of eelgrass habitat in Menemsha Pond (Section VIII-2).

Overall, it appears that the Menemsha-Squibnocket Embayment System has slightly exceeded its assimilative capacity for nitrogen with the resulting recent gradual decline in eelgrass coverage and, in historically non-eelgrass areas (e.g. Squibnocket Pond), impairment of benthic animal habitat. Determining the nitrogen target to restoring the impaired eelgrass habitat and protecting infauna habitat in the inner basins is the focus of the nitrogen management threshold analysis, below in Section VIII.2.

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(s) and 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.

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Menemsha-Squibnocket 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 Menemsha-Squibnocket Embayment System presently shows a moderate to significant level of impairment to eelgrass habitat primarily within Nashaquitsa Pond and Stonewall Pond, respectively. The impairment is based upon the recent temporal trend in loss of eelgrass from these basins and possible loss in the deeper region of Menemsha Pond main basin. Both the location and the temporal trend is consistent with nitrogen enrichment. However, that the rate of loss has been gradual and relatively recent (post 1995) indicates that this estuary is only just beyond its nitrogen threshold (i.e. the level of nitrogen a system can tolerate without impairment). The presence of stable dense eelgrass beds throughout the outer basins of Menemsha Pond and Menemsha Creek and the generally high quality benthic animal habitat throughout the outer basins and only moderate impairment in the enclosed tributary basins also indicates a system only just beyond its threshold. The indication of impairment to eelgrass and infaunal animal habitat as recently observed, is supported by the observed levels of oxygen depletion/excursion, clearly enhanced total pigment levels in the 3 enclosed basins and the organic enriched fine sediment with only thin surficial oxidation. These basins also have communities dominated by organic tolerant benthic animal species.

The spatial distribution of high quality and impaired habitats and associated oxygen and total pigment levels also parallels the gradient in water column total nitrogen levels within this estuary. The tidally averaged total nitrogen levels were observed to be 0.355 mg N L^{-1} within the main basin of Menemsha Pond (lower in the Creek) and much higher in the tidally restricted Squibnocket Pond, 0.789 mg N L^{-1}. The relatively low levels of nitrogen associated with the basins of Menemsha Pond are consistent with the generally high quality of eelgrass and benthic animal habitat within this system, but the clear enrichment in the areas losing eelgrass is consistent with the low level of impairment documented for this estuary. Similarly, the impaired benthic animal habitat in Squibnocket Pond is in the regions with largest oxygen depletions, phytoplankton blooms and accumulations of macroalgae. These regions support soft organic rich muds with only a thin oxidized surface layer and communities that are productive but clearly impaired as seen in their diversity, Evenness and low-moderate number of species dominated by organic tolerant species, including areas dominated by amphipods.

Restoring the impairments to eelgrass and protecting/restoring benthic animal habitat is the focus of the nitrogen management threshold analysis (Section VIII.3). As eelgrass within the Menemsha-Squibnocket Embayment System is a critical habitat that structures the productivity and resource quality of the entire system, and it is presently showing moderate to significant impairment primarily in Nashaquitsa Pond and Stonewall Pond and less so in Menemsha Pond, restoration of this resource is the primary target for overall repair of the Menemsha Pond portion of the overall system. Nutrient management planning for restoration of the eelgrass habitat associated with the component basins to Menemsha Pond should focus on reducing the level of nitrogen enrichment in main basin waters through watershed nitrogen management and managing tidal exchange as appropriate.

Based upon the information above, details provided in Section VII and the level of eelgrass impairment observed, it appears that the system is presently only slightly beyond its nitrogen threshold for sustainable eelgrass coverage. This assessment is based upon several factors as follows: 1) the distribution of the remaining eelgrass habitat, 2) the observed loss of eelgrass in Stonewall Pond, the deep basin of Nashaquitsa Pond and to a less extent Menemsha Pond, 3) that the decline has been gradual and relatively recent and 4) that the system is only moderately nitrogen and organic matter enriched. The impaired benthic animal habitat in Squibnocket Pond is the focus of nitrogen management of that basin (see below), as it has not historically supported eelgrass habitat.

The decline in eelgrass within the enclosed basin of Menemsha Pond and its tributary basins is consistent with its total pigment (8-20 ug L^{-1}) and tidally averaged total nitrogen (0.355 mg L^{-1}) levels. The tidally averaged total nitrogen (0.355 mg L^{-1}) level in areas just beginning to show eelgrass loss are consistent with the pattern of gradual loss overtime as TN concentrations increase. These TN levels and habitat stability/decline are consistent with persistence and loss of eelgrass at similar depths in other estuaries in southeastern Massachusetts.

For example, with the Nantucket Harbor Estuary, tidally averaged levels in the lower reach of Head of the Harbor (0.340-0.353) were associated with recent loss of eelgrass coverage, while eelgrass was lost from West Falmouth Harbor when tidally averaged TN exceeded 0.35 mg L^{-1}. The recent relatively small loss (as a percentage of total coverage) of eelgrass from Quissett Harbor was associated with tidally averaged nitrogen (total nitrogen, TN) levels of 0.354 mg N L^{-1}, while the Outer Basin high quality eelgrass habitat is at lower TN levels, 0.304 mg N L^{-1}. A threshold for tidally averaged TN at the sentinel station in the Inner Basin of Quissett Harbor (QH-2) of 0.34 mg was selected to restore eelgrass habitat.

In Megansett Harbor stable eelgrass coverage was determined to require a threshold for tidally averaged TN at the sentinel station (MG-2, Figure VI-1) of 0.35 mg N L^{-1}, based upon measurements of eelgrass habitat quality based upon the depth and TN levels within the stable eelgrass beds. This threshold is similar to that which was developed for West Falmouth Harbor and Phinneys Harbor, and is focused in part on restoring eelgrass where it had persisted until recently. Given the similarity in basin configuration, timing and extent of eelgrass loss, summertime chlorophyll and oxygen levels, the MEP Technical Team determined that the threshold to restore eelgrass within the Menemsha Pond basins is 0.35 mg N L^{-1} at the composite sentinel station in the main basin of Menemsha Pond. 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 protecting and improving infaunal habitats throughout Menemsha Pond. Therefore, the goal is to achieve the nitrogen target at the sentinel location and restore the historical eelgrass habitat within Menemsha Pond, resulting also in the protection and improvement of infaunal habitat throughout the System.

Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fisheries resources), benthic infaunal habitat quality must also be supported. Therefore, a second threshold was established for the restoration of the impaired benthic animal habitat within Squibnocket Pond, as it has not historically supported eelgrass habitat. Benthic animals are more tolerant of nutrient and organic matter enrichment than eelgrass, which requires clear waters and high oxygen levels. At present, in the regions supporting moderately to significantly impaired infaunal habitat within the Squibnocket Pond average tidal total nitrogen (TN) levels of 0.789 mg N L^{-1}. The observed impairments throughout this estuary are consistent with observations by the MEP Technical Team in other estuaries in the region (for example, Perch Pond, Bournes Pond, Popponesset Bay, Parkers River, upper Bass River, upper Great Pond, upper Three Bays, Rands Harbor and Fiddlers Cove). Based on these previous MEP assessments it has been determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat. In these estuaries levels <0.5 mg N L^{-1} were found to be supportive of healthy infaunal habitat and moderately impaired habitat was found at ~0.6 mg N L^{-1}. Similarly, moderate impairment was also observed at TN levels (0.535-0.600 mg N L^{-1}) within the Wareham River Estuary, while the Centerville River system showed moderate impairment at tidally averaged TN levels of 0.526 mg N L-1 in Scudder Bay and at 0.543 mg TN L-1 in the deep middle reach of the Centerville River.

Based upon these observations, the MEP Technical Team concluded that an upper limit of 0.50 mg N L^{-1} tidally averaged TN would support healthy infaunal habitat and 0.60 mg N L^{-1} would be supportive of moderate quality habitat in Squibnocket Pond. Further, the MEP Technical Team determined that achieving a level of 0.50 mg N L^{-1} in Squibnocket Pond was not possible by watershed nitrogen management alone. The highly restricted tidal channel from Squibnocket to Menemsha Pond does not provide sufficient flushing to maintain threshold nitrogen levels under non-anthropogenic loads (includes atmospheric N deposition). It appears that an increase in tidal flushing will be needed to achieve the threshold or an in pond nitrogen removal approach. Increased tidal flushing could be achieved through alteration of the herring run to carry more tidal flow or a periodic breaching of the barrier beach such as done in Edgartown Great Pond and other non-tidal salt ponds on Martha's Vineyard.

The nitrogen loads associated with the threshold concentration at the Menemsha Pond and Squibnocket Pond composite sentinel locations 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 Menemsha Squibnocket 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 Menemsha and Squibnocket Ponds. 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. A comparison between present septic and total watershed loading and the loadings for the two modeled threshold scenarios is provided in Tables VIII-2 and VIII-3.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations for Menemsha Pond required more than 50% removal of septic load (associated with direct groundwater discharge to the embayments) for the entire system. 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 Menemsha Squibnocket system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Menemsha			
Lower Creek	0.37	0.37	0.0%
Pease Point Brook	0.60	0.60	0.0%
Nashaquitsa Pond	3.07	0.61	-80.0%
Menemsha Creek	3.70	1.67	-55.0%
Menemsha Main	1.79	0.36	-80.1%
Squibnocket			
Black Brook	0.33	0.33	0.0%
Squibnocket East	0.50	0.50	0.0%
Squibnocket Main	1.25	0.81	-35.2%
System Total	11.60	5.24	-54.9%

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. For example, removal of 80% of the septic load from the Nashaquitsa Pond watershed results in a 60% reduction in total watershed nitrogen load for the same watershed. No load reductions were necessary for the Lower Creek and Pease Brook watersheds in Menemsha and Black Brook and Squibnocket East watersheds in Squibnocket. 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 Vineyard Sound, as discussed in Section VI.2.6.1.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. The TN concentration to achieve eelgrass restoration in the Menemsha Pond (inclusive of Stonewall and Nashaquitsa Ponds) is 0.35 mg N L^{-1} and to restore benthic animal communities in Squibnocket Pond is 0.5 mg L^{-1}, as discussed above (Section VIII-2). To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN concentrations of typically less than 20% was required in the system, between the Menemsha Creek and Main Basin as well as Nashaquitsa Pond. It should be noted that achieving the threshold in Squibnocket Pond is not possible due to the presently configured channel (Herring Run) between Menemsha and Squibnocket Ponds. Complete removal of controllable nitrogen loads into Squibnocket Pond is insufficient to lower the TN concentration to the threshold level. This was expected as the channel is highly restricted with two flow control structures, a narrow culvert, and narrow channel widths resulting in very low tidal exchange and flow volumes. In these cases, for example in Rushy Marsh or some periodically opened salt ponds, it is difficult to impossible to achieve the threshold without reconfiguring the tidal inlet or breaching protocols. In the case of Squibnocket Pond the tidal prism would need to be increased by 20 to 25 times to meet the threshold for Squibnocket Pond. The feasibility of reconfiguring or replacing the flow control structures and culvert would need to be evaluated to determine the most appropriate solution to meet the threshold while preserving the Herring Run.

Table VIII-3. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Menemsha Squibnocket 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
Menemsha			
Lower Creek	0.46	0.46	0.0%
Pease Point Brook	0.84	0.84	0.0%
Nashaquitsa Pond	4.07	1.62	-60.3%
Menemsha Creek	4.60	2.56	-44.3%
Menemsha Main	2.73	1.30	-52.4%
Squibnocket			
Black Brook	0.56	0.56	0.0%
Squibnocket East	0.75	0.75	0.0%
Squibnocket Main	2.03	1.59	-21.6%
System Total	16.04	9.68	-39.7%

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.

The basis for the watershed nitrogen removal strategy utilized to achieve the system threshold may have merit, since this example of a nitrogen remediation approach is focused on watersheds where groundwater is flowing directly into the estuary. 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. Streams, 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-4. Threshold sub-embayment loads used for total nitrogen modeling of the Menemsha Squibnocket 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)
Menemsha			
Lower Creek	0.460	--	--
Pease Point Brook	0.844	--	--
Nashaquitsa Pond	4.074	1.668	0.972
Menemsha Creek	4.600	1.419	0.292
Menemsha Main	2.729	8.553	50.164
Squibnocket			
Black Brook	0.559	--	--
Squibnocket East	0.751	1.118	--
Squibnocket Main	2.027	7.890	8.220
System Total	16.044	20.649	59.648

Table VIII-5. Comparison of model average total N concentrations from present loading and the **threshold scenario**, with percent change over offshore at Menemsha Pond tidal inlet (0.287 mg/L), for the Menemsha Squibnocket system. The threshold (o.50mg/l) in Squibnocket pond could not be met by load reduction.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Menemsha Creek Low	MEN 1	0.296	0.295	-6.9%
Menemsha Creek Low	MEN 2	0.304	0.302	-9.6%
Menemsha Main Basin	MEN 3	0.311	0.309	-8.8%
Menemsha Main Basin	MEN 4	0.404	0.398	-5.4%
Nashaquitsa Mouth	MEN 5	0.335	0.329	-11.9%
Nashaquitsa Basin	MEN 6	0.347	0.337	-16.7%
Menemsha Main Basin	MEN 8	0.368	0.363	-6.1%
Menemsha Main Basin	MEN 9	0.358	0.354	-6.3%
Menemsha Creek	MEN 10	0.308	0.306	-9.0%
Menemsha Sentinel	**MEN 4,5,8,9,10**	**0.355**	**0.350**	**-7.4%**
Squibnocket Basin	SQ 1	0.761	0.756	-1.1%
Squibnocket Basin	SQ 2	0.793	0.789	-0.9%
Squibnocket Basin	SQ 3	0.786	0.782	-0.9%
Squibnocket Basin	SQ 4	0.817	0.813	-0.8%
Squibnocket Sentinel	**SQ 1-4**	**0.789**	**0.785**	**-0.9%**

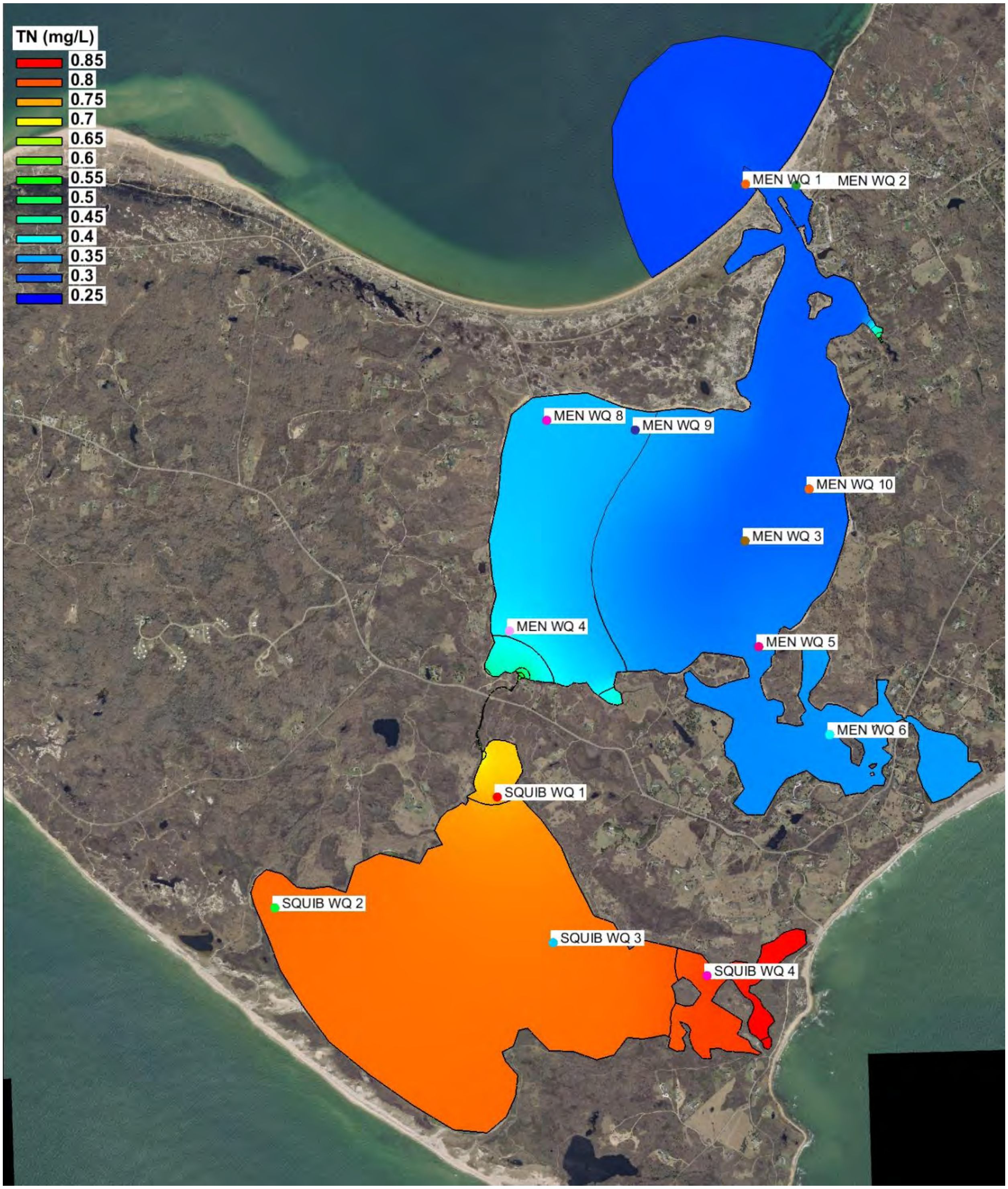

Figure VIII-1. Contour plot of tidally averaged modeled total nitrogen concentrations (mg/L) in the Menemsha Squibnocket system, for threshold.

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