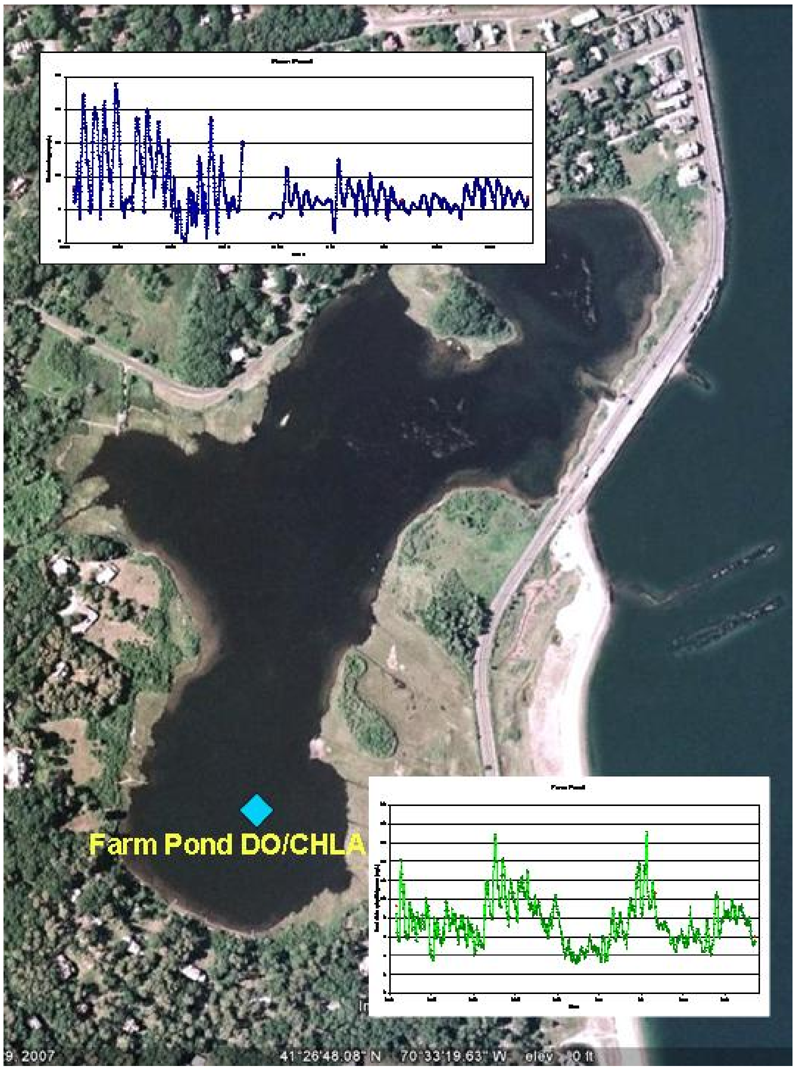
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Farm Pond System, Town of Oak Bluffs, MA



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

FINAL REPORT – November 2010

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Brian Howes
Roland Samimy
David Schlezinger
Ed Eichner

Sean Kelley
John Ramsey

Phil "Jay" Detjens

Contributors:

US Geological Survey

Don Walters and John Masterson

Applied Coastal Research and Engineering, Inc.

Elizabeth Hunt and Trey Ruthven

Massachusetts Department of Environmental Protection

Charles Costello and Brian Dudley (DEP project manager)

SMAST Coastal Systems Program

Jennifer Benson, Michael Bartlett, and Sara Sampieri

Cape Cod Commission & Martha's Vineyard Commission

Tom Cambareri William Wilcox

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

Massachusetts Department of Environmental Protection

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Executive Summary

1. Background

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Farm Pond embayment system, a coastal embayment entirely within the Town of Oak Bluffs, Massachusetts. Analyses of the Farm Pond embayment system was performed to assist the Town of Oak Bluffs with up-coming nitrogen management decisions associated with the current and future wastewater planning efforts of the Town, as well as wetland restoration, anadromous fish runs, shell fishery, and open-space management programs. As part of the MEP approach, habitat assessment was conducted on the embayment based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Town of Oak Bluffs resource planning and decision-making process. The primary products of this effort are: (1) a current quantitative assessment of the nutrient related health of the Farm Pond embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Town) for the restoration of the Farm Pond embayment system.

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

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

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

The Town of Oak Bluffs has recognized the severity of the problem of eutrophication and the need for watershed nutrient management and is currently engaged in wastewater management at a variety of levels. Moreover, the Town of Oak Bluffs is working collaboratively with the Town of Edgartown relative to the MEP nutrient threshold analysis of the Sengekontacket Pond system to the south of the Farm Pond system. In this manner, this analysis of the Farm Pond system will be considered relative to the recently completed nutrient threshold analysis of Sengekontacket Pond to plan out and implement a unified town-wide approach to nutrient management for Oak Bluffs. The Town of Oak Bluffs with associated working groups have recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making and alternatives analysis. The completion of this multi-step process has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, which is a partnership effort between all MEP collaborators and the Towns in the study region. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns' nutrient management groups to predict the impacts on water quality from a variety of proposed management scenarios.

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

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

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

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

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

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

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

Application of MEP Approach: The Linked Model was applied to the Farm Pond embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Martha's Vineyard Commission and the Town of Oak Bluffs. The water quality monitoring program was conducted with technical guidance from the Coastal Systems Program at SMAST (see Chapter II). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Oak Bluffs Planning Department and the Martha's Vineyard Commission. The MEP technical team reviewed the sub-regional groundwater model originally prepared by Whitman Howard (1994) and the subsequent update by Earth Tech in order to obtain up to date watershed delineations. This model organized much of the historic USGS geologic data collected on Martha's Vineyard and provided a satisfactory basis for incorporating the MEP refinements necessary to complete the Farm Pond watershed delineation. The watershed boundaries were confirmed by the by the USGS. This watershed delineations and the land-use data was used to determine watershed nitrogen loads within the Farm Pond embayment system and each of the systems sub-embayments as appropriate (current and build-out loads are summarized in Chapter IV). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Farm Pond embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Vineyard / Nantucket Sound source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Farm Pond embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the embayments.

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

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

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Farm Pond embayment system in the Town of Oak Bluffs. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment, however, within this report an additional hydrodynamic analysis was completed on a culvert widening scenario to improve tidal flushing. Using the calibrated hydrodynamic model of Farm Pond, four inlet scenarios were modeled to evaluate how different inlet widths would impact the tidal characteristics of the Pond. Each modeled scenario was run with the inlet in its present location under Beach Road.

The MEP analysis has initially focused upon nitrogen loads from on-site septic systems as a test of the potential for achieving the level of total nitrogen reduction for restoration of each embayment system. The concept was that since nitrogen loads associated with wastewater generally represent 70% of the controllable watershed load to the Farm Pond embayment system and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through this source is a good gauge of the feasibility for restoration of these systems.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Farm Pond embayment system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure. At present, the Farm Pond Estuary is showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Chapter VII). For the purposes of this analysis Farm Pond was separated into a northern basin roughly above Woody Island and a larger southern basin south of Woody Island. Overall, the system is showing some nitrogen related habitat impairment throughout the tidal reach. While there is little horizontal gradient in water quality parameters within Farm Pond due to horizontal mixing, there is a clear gradient of declining habitat quality moving from south to north. The north basin is a significantly impaired basin relative to eelgrass. Although the basin presently supports sparse eelgrass coverage, the sparse patchy coverage indicates significant impairment. In contrast, the relatively dense eelgrass beds in the southern basin which appear to be declining only slightly are moderately impaired.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels within Farm Pond indicate moderate levels of nutrient enrichment and impaired habitat quality. The oxygen data are consistent with high organic matter loads from phytoplankton production and the large daily excursions in oxygen concentration also indicate significant organic matter enrichment.

Generally, the dissolved oxygen records indicate moderate depletions during the critical summer period, but with periodic significant depletions, hypoxia (<4 mg L^{-1}), of bottom waters. Oxygen records indicate that the basin of Farm Pond frequently has oxygen levels in the 4-6 mg L^{-1} range, and infrequently to the highly stressful <2 mg L^{-1} levels. These observed levels of oxygen depletion are consistent with the moderate chlorophyll levels coupled to the tidally restricted nature of the system and the very warm waters (average 24 C, maximum 28 C) which stimulate the rates of oxygen uptake in the water column and sediments. Overall, the pattern of high nitrogen, resulting in moderate levels of phytoplankton biomass with periodic blooms and periodic low oxygen depletion was found throughout this system.

In all areas and particularly those that do not support eelgrass beds, benthic animal indicators are 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 survey of infauna communities throughout Farm Pond indicated a system presently supporting impaired benthic infaunal habitat. Infaunal habitat within the northern basin is severely degraded, based upon the very low numbers of animals present (~20 per sample) and few species (5 per sample). The southern basin, while supporting a higher habitat quality, is still significantly impaired. The designation of significant impairment stems from the presence of higher numbers of individuals and species, but a community dominated by stress tolerant species indicative of high levels of organic enrichment.

There is a general increase in habitat impairment moving from south to north within Farm Pond. This trend is seen both in eelgrass and infaunal habitat quality. The observed infaunal communities are consistent with the frequent summertime hypoxia in bottom waters and the organic rich soft sediments with only a thin oxidized surface layer. The tidally averaged total nitrogen levels in Farm Pond waters (0.48-0.51 mg N L^{-1}) presently are at the typical upper threshold for high quality benthic habitat, and the observed degree of impairment is generally seen at higher nitrogen levels. However, the evidence of impairment is clear and shows little variation within sites.

At present, eelgrass exists across a relatively large portion of the system, particularly in the south basin. The apparent slight decline in the aerial distribution of eelgrass beds in Farm Pond from 1997 to 2006 is expected given the observed nitrogen levels and resulting chlorophyll-*a* and dissolved oxygen depletions within this embayment system.

The condition of the eelgrass bed observed in 2006 by SMAST/MEP Technical Team members is also consistent with the observed moderate level of nutrient enrichment across the three water quality monitoring stations that represent nutrient levels throughout the pond. Field observations by SCUBA diver of the eelgrass beds during the sediment survey indicated high coverage by epiphytes in some areas and only sparse patchy eelgrass colonization within the north basin. These observations mirrored measured epiphyte growth by the MV Commission and observations of sparse eelgrass in the north basin in 2006 by the Town of Oak Bluffs Shellfish Department.

3. Conclusions of the Analysis

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

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

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Town of Oak Bluffs Farm Pond embayment system was comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 70% of the controllable watershed nitrogen load to the embayment was from wastewater.

A major finding of the MEP clearly indicates that a single general total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of the Great, Green and Bournes Pond Systems, Popponesset Bay System, the Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay and the analysis of the nearby Sengekontacket Pond system as well as Lagoon Pond and Edgartown Great Pond. This is almost certainly going to continue to be true for the other embayments within the MEP area, as well, inclusive of Farm Pond.

The threshold nitrogen levels for the Farm Pond embayment system in Oak Bluffs were determined as follows:

Farm Pond Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Farm Pond system should reflect both recent pre-degradation habitat quality and be reasonably achievable. Based upon the assessment data (Chapter VII), the Farm Pond system is presently supportive of habitat in varying states of impairment, depending on the component sub-basins of the overall system (e.g. north basin above Woody Island or south basin below Woody Island).

- The primary habitat issue within the Farm Pond Embayment System relates to the general loss of eelgrass beds from the north basin above Woody Island. The Farm Pond Embayment System presently supports nitrogen related habitat impairment throughout the tidal reach. While there is little horizontal gradient in water quality parameters within Farm Pond due to horizontal mixing, there is a clear gradient of declining habitat quality moving from south to north. The north basin is significantly impaired basin relative to eelgrass, as it has only sparse patchy eelgrass coverage. In contrast, the relatively dense eelgrass beds in the southern basin, which appear to be declining only slightly, are moderately impaired. The moderate impairment designation stems from the apparent reduction in coverage and the observed moderate density of epiphytes on the eelgrass blades (Section VII-2). Similarly, the basins have impaired infauna habitat, with severely degraded habitat in the northern basin, which is virtually devoid of animals, and significantly degraded habitat in the southern basin which has moderate numbers of animals, but is dominated (50%) by the organic enrichment tolerant species, *Capitella capitata* (Section VII-3).

- The eelgrass and water quality information supports the conclusion that eelgrass beds within the entire main basin should be the primary target for restoration of the Farm Pond Embayment System and that restoration requires a reduction in nitrogen enrichment through appropriate watershed nitrogen management and/or increased tidal exchange. As the south basin has slightly higher TN levels than other regions of Farm Pond, the sentinel station for the Farm Pond Estuary is the southern most long-term water quality monitoring station (FRM-3, Section VI). Presently, the sentinel station has a tidally averaged TN of 0.51 mg L-1, consistent with the observed epiphyte growth on the eelgrass and apparent decline in coverage.

- The levels of TN and quality of the eelgrass habitat observed in Farm Pond are comparable to similar shallow systems in the region, where at these TN levels the eelgrass is stressed, has epiphytes and is just beyond its tolerance limit. Taking into consideration the information above, the depth of Farm Pond, its moderate level of eelgrass impairment and TN levels of 0.48 - 0.51 mg L^{-1}, it appears that the system is presently slightly beyond its nitrogen threshold for sustainable eelgrass coverage. This assessment is based upon the fact that eelgrass presently colonizes much of the main basin and that epiphyte growth is moderate and there has been little recent loss of bed coverage.

- To restore eelgrass habitat in Farm Pond the nitrogen concentration (tidally averaged TN) at the sentinel location within the southern basin needs to be lowered to 0.45 mg TN L^{-1}. This threshold levels is consistent with high quality shallow water eelgrass habitat observed in Bournes Pond on Cape Cod and is similar to the condition of eelgrass within the Parker's River system in the Town of Yarmouth, both with a tidally averaged TN level of 0.45 mg TN L^{-1}. The TN threshold for Farm Pond represents a relatively high threshold as a result of the shallow depth of the entirety of the potential eelgrass habitat. The goal, to achieve the nitrogen target at the sentinel location and restore quality eelgrass habitat within Farm Pond, will also result in the restoration of infaunal habitat throughout the System. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations are discussed in Section VIII.3.

For restoration of the Farm Pond Embayment System, the primary nitrogen threshold at the sentinel station will need to be achieved. At the point that the threshold level is attained at the sentinel station, water column nutrient concentrations will also be at a level that will be supportive of healthy infaunal communities. The results of the Linked Watershed-Embayment modeling are used to ascertain that when the nitrogen threshold is attained, TN levels in the regions associated with the secondary criteria of healthy infauna are also within an acceptable range. The goal is to achieve the nitrogen target at the sentinel location and restore healthy eelgrass habitat throughout lower and upper region of the Farm Pond system as well as infaunal habitat throughout the embayment.

It is important to note that the analysis of future nitrogen loading to the Farm Pond estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that significant increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. Therefore, watershed-estuarine nitrogen management must include management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Farm Pond estuarine system is that restoration will necessitate a reduction in the present (2008) nitrogen inputs and management options to negate additional future nitrogen inputs.

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

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
Farm Pond System Total	0.72	1.548	4.060	0.362	5.970	0.490	-0.892	5.568	**0.51-0.53**	**0.50**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing attenuated wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings (the sum of land use, septic, and WWTF loading)
[5] atmospheric deposition to embayment surface only.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of data collected between 2002 and 2008, ranges show the upper to lower regions (highest-lowest) of the indicated sub-embayment.
[8] threshold for sentinel site located at mid-point WQ monitoring station of the system.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Farm Pond system.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent change in watershed load to achieve allowed threshold load levels
Farm Pond System Total	5.970	4.394	0.490	-0.751	4.133	-26.4%

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

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

First and foremost we would like to recognize and applaud the significant time and effort in data collection and discussion spent by members of the Martha's Vineyard Commission and the Town of Oak Bluffs Shellfish Department's Water Quality Monitoring Program. These individuals gave of their time to develop a consistent and sound baseline of nutrient related water quality for this system, without which the present analysis would not have been possible. Also, the Friends of Farm Pond were helpful by posting historical information available via their web site and educating the public.

Staff from the Martha's Vineyard Commission and the Town of Oak Bluffs and volunteers from the Friends of Farm Pond have provided essential insights toward this effort. Of particular note has been the efforts of Dave Grunden (Oak Bluffs Shellfish Constable) and Bill Wilcox (MVC Water Resource Planner), who has spent countless hours reviewing data and information with MEP Technical Team members in support of the MEP analysis of Farm Pond. In addition, Chris Seidel, GIS Specialist from the MVC, provided significant support for the MEP land-use analysis, particularly analysis of parcel information and site-specific loading information (e.g. related to wastewater disposal.

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

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I. INTRODUCTION

The Farm Pond Embayment System is a simple estuary located within the Town of Oak Bluffs on the island of Martha's Vineyard, Massachusetts. This estuary presently exchanges tidal waters with Nantucket Sound via two culverts through its eastern shore (Figure I -1). Tidal flushing of this system has been highly altered over the past 150 years by storms and human alteration, most recently the opening of a second culvert (October 15, 2009) which stayed open for only one week. Tidal exchange is essential to maintaining habitat quality of estuaries, as restrictions to tidal exchange increase the sensitivity of these systems to the negative effects of nitrogen loading. Nitrogen loading to the Farm Pond watershed is primarily from residential development with little nitrogen stemming from the undeveloped land that comprises a portion of the upper watershed area. Unlike the watersheds to most estuaries in southeastern Massachusetts, the watershed to Farm Pond does not contain any large freshwater ponds. Freshwater ponds and wetlands reduce nitrogen passing through during transport from upgradient sources to the down gradient estuarine waters. Effective restoration of the Farm Pond System will require consideration of all sources of nitrogen load relative to rates of tidal exchange with Nantucket Sound.

As the entire watershed and estuarine waters of the Farm Pond system are contained within a single municipality, the Town of Oak Bluffs, this should streamline the development and implementation of a comprehensive nutrient management and restoration plan for the pond, since inter-municipal issues of load allocation and timing are absent.

The nature of enclosed embayments in populous regions brings two opposing elements to bear: As protected marine shoreline they are popular regions for boating, recreation, and land development; as enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shores. In drowned river valley estuaries, which have significant stream inflows, the groundwater travel time is greatly reduced resulting in rapid responses in estuarine habitat quality with changes in watershed loading. In contrast, lagoonal estuaries without significant surface water inflows and watershed freshwater discharge dominated by groundwater, inflows can have proportionally longer groundwater travel times. For example, Sengekontacket Pond has tributary coves (e.g. Majors Cove and Trapps Pond) that greatly increase its shoreline, but with much less effect on groundwater travel time and discharge of its pollutants stemming from watershed recharge areas. In both cases the ability of the estuary to tolerate nitrogen and other pollutant inputs is directly related to the embayment structure and rates to tidal exchange. However in general, lagoonal estuaries in southeastern Massachusetts typically have smaller watersheds than drowned river valley estuaries and as such, estuarine response can still be rapid as nitrogen management alternatives are implemented. However, groundwater travel times must be evaluated on a system by system basis.

Farm Pond is a lagoonal estuary, an enclosed tidal basin formed behind a barrier beach and running parallel to the coastline, similar to Sengekontacket Pond to the south. Its watershed does not currently support any major streams. Historically there were some small fresh water tributaries/reaches and as recently as the 1960's there was a small alewife run. Currently however, these historic surface water features are overgrown and choked mostly by Phragmites. As such, recharged groundwater discharges directly to the estuarine waters primarily along its inland shoreline. Its lack of tributary basins and centrally located tidal inlet tends to reduce gradients in nutrient related habitat quality within the basin.

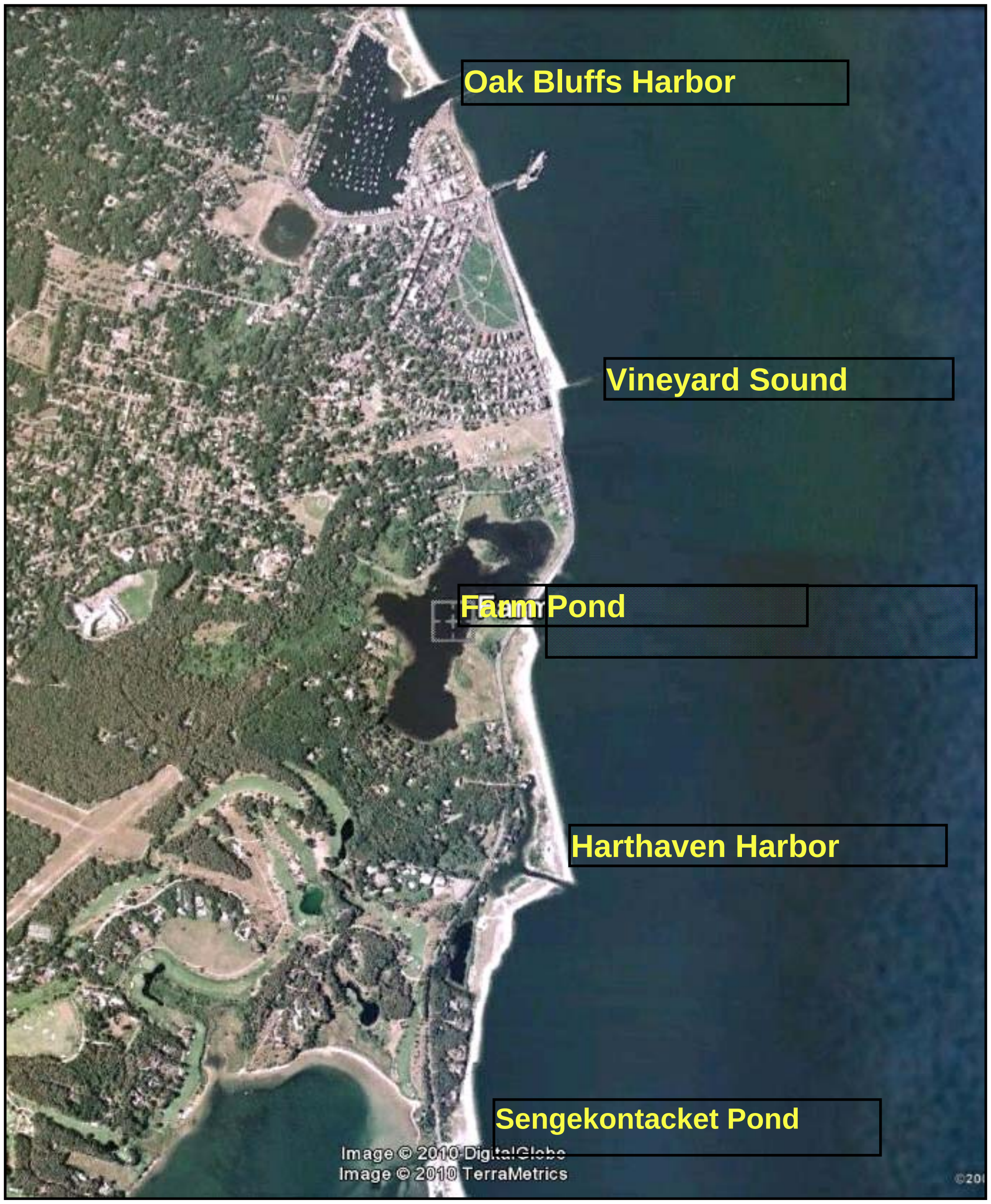


Figure I-1. Location of the Farm Pond System, Island of Martha's Vineyard, Town of Oak Bluffs, Massachusetts. Farm Pond is a great salt pond, with a tidal inlet through the barrier beach and a second inlet (culvert) recently reopened (October 2009), which allow exchange of water with Vineyard / Nantucket Sound.

The tidal inlet from Farm Pond to Vineyard Sound is through an active barrier beach, which has resulted in periodic natural closures and openings and human alterations to "maintain" tidal flows. The alterations, generally to enhance tidal exchange, have been attempts to maintain Farm Pond's estuarine habitats and resources and they continue today. Maintenance of the tidal exchange to Farm Pond is one of the key management factors for this system, since its sensitivity to watershed nitrogen additions (e.g. eutrophication) is related to the rate of exchange with high quality Vineyard Sound waters.

Figure I-2. Study region for the Massachusetts Estuaries Project analysis of the Farm Pond Embayment System. Tidal waters enter the Pond from Vineyard Sound through a n existing culvert passing through the barrier beach at Beach Road, and the temporarily-opened relic culvert (October 2009) which soon after being opened was clogged by a storm and abandoned. At one time Harthaven Harbor ran from the jetties (remnants seen offshore in photo) to the southern basin of the present Harbor (Figure I-1). Freshwater enters from the watershed primarily through direct groundwater discharge as there are no significant surface water inflows to this system. The island (Woody Island) was "created" by putting a channel through the base of what was a peninsula. Farm Pond is a highly man-altered system behind a very dynamic barrier beach.

The primary ecological threat to the Farm Pond embayment system, as is the case for virtually all other estuaries in southeastern Massachusetts, is degradation resulting from nutrient over-enrichment. Although the watershed and the Pond have issues relative to bacterial contamination, this does not appear to be having large ecosystem-wide impacts. 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 Farm Pond System results in both habitat impairment and loss of the resources themselves. Within the Farm Pond watershed, 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, results primarily from on-site disposal of wastewater and WWTF discharges, and to a lesser extent fertilizer use and stormwater flows. This is discussed in detail in Chapter IV.

The towns of Martha's Vineyard have been among the fastest growing towns in the Commonwealth over the past two decades and while the Town of Oak Bluffs does have a "centralized" wastewater treatment system, only a portion of the Farm Pond watershed is connected to this municipal sewerage system. As such, most of the homes within the Farm Pond watershed rely on privately maintained septic systems for on-site treatment and disposal of wastewater. This type of system for handling residential wastewater in turn contributes to the nitrogen loading to the estuary via groundwater discharge. As existing and probable increasing levels of nutrients impact the coastal embayments of the Town of Oak Bluffs, water quality degradation will accelerate, with further harm to invaluable environmental resources of the Town and the Island on the whole.

As the primary stakeholder to the Farm Pond system, the Town of Oak Bluffs, in collaboration with the Martha's Vineyard Commission (MVC), has been among the first communities to become concerned over perceived degradation of its coastal embayments. The importance of Farm Pond to the citizens of Oak Bluffs can be seen in the formation in 2005 of a citizen stewardship group, The Friends of Farm Pond, who have been active in promoting restoration of this estuary. As a result of the concerns of these various groups and agencies a variety of studies have been undertaken relative to the health of this estuary, particularly associated with tidal flushing (Chapter II). Moreover, the Town of Oak Bluffs successfully nominated Farm Pond to be placed on the Massachusetts' Wetland Restoration Priority List" in 2004.

One key development for the management of this system was the inclusion of Farm Pond into the water quality monitoring program of Martha's Vineyard's estuaries and salt ponds conducted by the Martha's Vineyard Commission (Bill Wilcox). The initial results of the Water Quality Monitoring Program (2003-2005) indicated that Farm Pond is showing the effects of nitrogen enrichment related to restricted tidal exchange and watershed nitrogen loading. As part of restoring this system, the Town of Oak Bluffs and the Martha's Vineyard Commission (MVC) undertook participation in the Massachusetts Estuaries Project to complete ecological assessment and water quality modeling for the development of nutrient thresholds for restoration of Farm Pond.

The common focus of the Town of Oak Bluffs - MVC collaborative efforts with the MEP Technical Team in the Farm Pond system has been to gather site-specific data on the current nitrogen related water quality and habitat quality throughout the pond system and determine its relationship to watershed nitrogen loads and tidal exchange. This multi-year effort of water quality monitoring and high-end data collection on habitat characteristics has provided the information required for determining the link between upland loading, tidal flushing, estuarine water quality and the quality of marine habitats. The MEP effort builds upon the Water Quality Monitoring Program, and previous hydrodynamic and water quality analyses, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the embayment as a whole. These critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater planning and nitrogen management alternatives development needed by the Towns of Oak Bluffs.

While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff and volunteers over many years, and most notably from members of the Martha's Vineyard Commission. The modeling tools developed as part of this program provide the quantitative information necessary for the Town of Oak Bluffs to develop and evaluate the most cost effective nitrogen management alternatives to restore this valuable coastal resource which is currently being degraded by nitrogen overloading. It is important to note that the Farm Pond System and its associated watershed have been significantly altered by natural and human activities over the past ~100 years. The major alteration affecting the systems response to nitrogen loads is associated with the dynamic nature of the barrier beach system and alteration of tidal exchange due to inlet closures/openings and attempts to manage tidal flows. These alterations subsequently affect the sensitivity of the Pond to nitrogen loading from its surrounding watershed. Therefore, restoration of this system should focus on managing nitrogen related habitat quality through both the management of watershed nitrogen loading and maintaining tidal exchange at appropriate levels.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

The primary nutrient causing the increasing impairment of the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within Southeastern Massachusetts alone, almost all of the municipalities (as is the case with the Town of Oak Bluffs) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries.

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

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

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

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

The major MEP nitrogen management goals are to:

- provide technical analysis and supporting documentation to Towns as a basis for sound nutrient management decision making towards embayment restoration
- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment’s model “alive” to address future municipal needs.

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

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

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

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

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

- 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 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

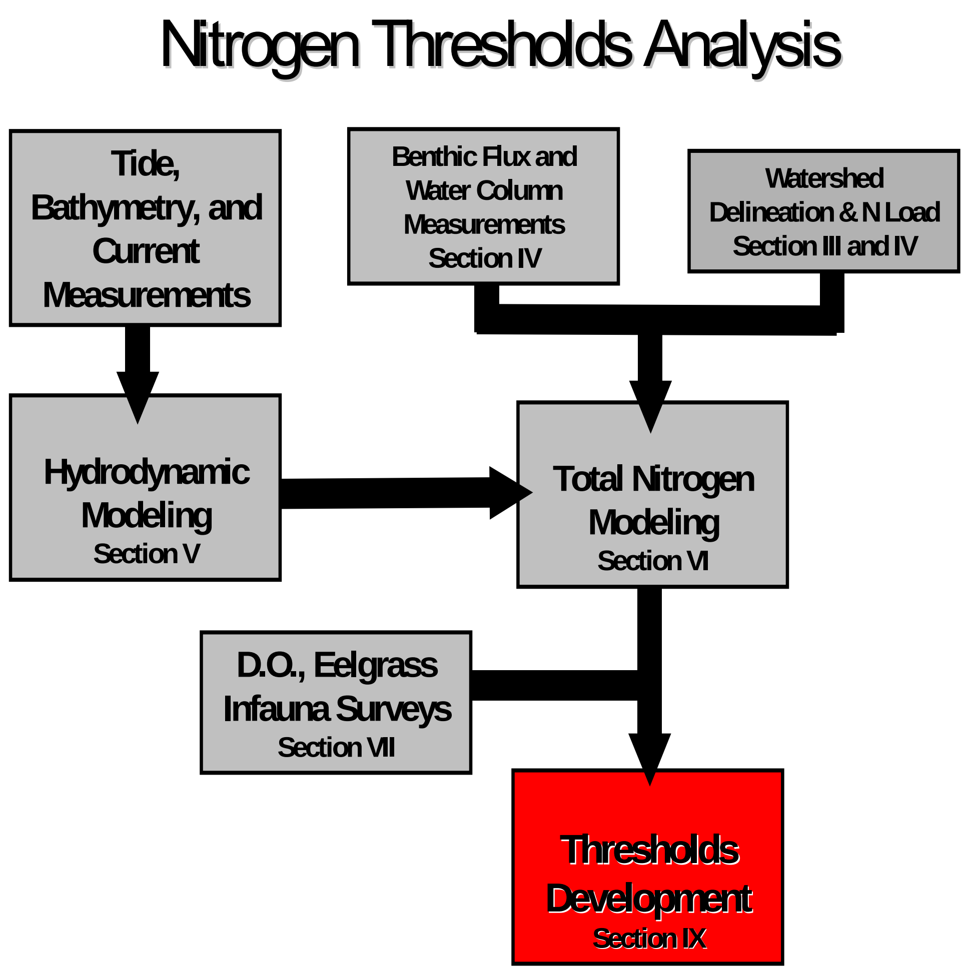


Figure I-3. Flow chart of key elements of the Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

I.2 SITE DESCRIPTION

Farm Pond is a 42 acre coastal salt pond at high water which includes approximately 8 acres of salt marsh. The Pond was derived from the old de Bettencourt Farm that once occupied its shores (Dunlop 2004). The pond is characterized by a single main basin with a small connected upper basin partially separated by an undeveloped island, Woody Island, which was detached from the upland by an artificial channel. The watershed to the pond is completely sited within the Nantucket Moraine sediments consisting mainly of folded pre-Wisconsin clay, sand, gravel and glacial till overlain by Wisconsin drift (Woodworth and Wigglesworth 1934). These sediments were deposited as the ice sheets retreated at the end of the last glacial period.

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

The enclosed Farm Pond estuary appears to have been formed as a lagoonal estuary, where a cove was enclosed by formation of a barrier beach due to sand deposition via coastal processes. Lagoonal estuaries form parallel to coastlines and are a major type of estuary along the east coast of the United States. It has been proposed that this system was formed by the drowning of a coastal kettle pond, which cannot be discounted. However, its shallow depth and the finding that beach deposits form its Vineyard Sound shoreline favor its formation as a "lagoon". What is clear is that it is presently functioning as an estuarine system and is showing signs of nitrogen enrichment. For the MEP analysis, the Farm Pond estuarine system was considered as one large basin with associated wetland areas in the northern and south-eastern reaches (see Figure I-2).

The Farm Pond Embayment System is a simple estuary or great salt pond, which has typically exchanged waters with Vineyard Sound through a single tidal inlet or culvert. However, recently (October 2009) a pre-existing second culvert was re-opened in an attempt to enhance tidal exchange. The "main" inlet/culvert passes under Beach Road and has been active since the 1980's when the previous tidal inlet, Harthaven Inlet, was abandoned due to frequent problems with shoaling and blockage which greatly reduced tidal flows. Floodwater enters from Vineyard Sound at mid basin and mixes throughout the pond, as can be seen in the lack of strong nutrient or salinity gradients within the pond (Chapter VI). Water from the Sound is occasionally introduced into Farm Pond through storm surges over topping Beach Road (Figure I-2).

The formation of the Farm Pond System has and continues to be greatly affected by coastal processes, specifically the role that the barrier beach plays in separating the pond from Vineyard / Nantucket Sound source waters. The ecological and biogeochemical structure of the pond is likely to have changed over time as the barrier beach naturally breached in different locations along the barrier beach and intermittently closed in as a function of storm frequency and intensity. Like many great salt ponds on Martha's Vineyard, humans have long attempted to dampen the ecological consequences of the natural cycling of pond closures and opening by artificially enhancing or sustaining tidal exchange. In the case of Edgartown Great Pond, this management of tidal exchange is through periodic openings to tidal flows, while in Farm Pond armored tidal inlets or culverts have been used. However, given the dynamic nature of the coastline associated with Farm Pond, tidal restrictions have historically occurred and there is evidence of periodic freshening of pond waters. More importantly, recent periods of tidal restriction have resulted in a magnification of watershed nitrogen inputs and nitrogen enriched pond waters, showing eutrophication related ecological responses. The potential resource value to the citizens of Oak Bluffs can be seen in the reports of blue crab, soft shell clam and oyster harvest as recently as the 1970's. Any management plan for Farm Pond must take into account the significant issue of sustaining tidal exchanges in addition to managing nitrogen loadings.

I.3 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 or in porous morainal aquifers, such as in the watersheds to the Edgartown Great Pond System and Farm Pond System, respectively, 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 reach within the Farm Pond System follows this general pattern, where the primary nutrient of eutrophication in the systems is nitrogen.

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

Each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation. However, as loading increases a point is reached at which the capacity (termed assimilative capacity) is exceeded and nutrient related water quality degradation occurs. This point can be termed the "nutrient threshold" and in estuarine management this threshold sets the target nutrient level for restoration or protection. Because nearshore coastal 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 inputs, tidal exchange and nitrogen concentrations throughout the Farm Pond System monitored by the Martha's Vineyard Commission and the Town of Oak Bluffs. The Water Quality Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) was utilized to "tune" general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, almost all of the Farm Pond System is near or beyond its ability to assimilate additional nutrients without impacting the ecological health of the overall system. Nitrogen levels are elevated throughout this salt pond and eelgrass beds have declined over the past fourteen years as noted by the MassDEP Eelgrass Mapping Program, the MVC and most recently the MEP Technical Team during the summer and fall of 2006. Nitrogen related habitat impairment within the Farm Pond Estuary shows a slight gradient with highest quality habitat closest to the tidal inlet and lowest quality habitat within the northern portion of the pond. The result is that nitrogen management of the Farm Pond system is aimed at protecting the eelgrass resource that still exists and restoring the adjacent areas of eelgrass habitat, where sparse eelgrass patches are only periodically observed.

In general, nutrient over-fertilization is termed "eutrophication" and in certain instances can occur naturally over long periods of time. When the nutrient loading is rapid and primarily from human activities leading to changes in a coastal watershed, nutrient enrichment of coastal waters is termed "cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to the systems of Martha's Vineyard and contributed to the degradation in ecological health within the Farm Pond System, the Pond is especially sensitive to nitrogen inputs because of fluctuations in tidal exchange with Vineyard / Nantucket Sound water resulting from inlet sedimentation. The quantitative role of the tidal restriction of this system was considered in detail in the MEP nutrient threshold analysis. As part of future protection/restoration efforts for Farm Pond, it is important to understand that nitrogen management will restore habitat health, but depending upon the approaches employed, may not eliminate the periodic bacterial contamination of pond waters.

I.4 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 Farm Pond System; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within each system. Therefore, water quality modeling of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. The spread of pollutants may be analyzed from tidal current information developed by the numerical models.

The MEP water quality evaluation examined the potential impacts of nitrogen loading into the Farm Pond System. Given the shallowness of the Pond and generally well vertically mixed nature of the water column, a two-dimensional depth-averaged hydrodynamic model based upon the tidal currents at the single inlet/culvert to the pond system and water elevations was employed for the hydrodynamic analysis of the entire Farm Pond system. Once the hydrodynamic properties of each component of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon MEP refined (working with the USGS and MVC) watershed delineations originally developed by Earth Tech. Almost all nitrogen entering the Farm Pond System is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Farm Pond waters were collected by the Town of Oak Bluffs/MVC Water Quality Monitoring Program (a coordinated effort between the Towns of Oak Bluffs, the Martha's Vineyard Commission and the Coastal Systems Program at SMAST). Salinity and total nitrogen in inflowing Vineyard Sound waters were from the Nantucket Sound Monitoring Consortium surveys (2006-08) overseen by the Coastal Systems Program at SMAST. Measurements of nitrogen and salinity distributions throughout estuarine waters of the system (2003-2009) were used to calibrate and validate the water quality model (under existing loading conditions). The tidal flushing conditions for this analysis were based on a single inlet configuration, as existed prior to October 2009. The effect of different inlet configurations was evaluated as "scenario runs" using the calibrated and validated models.

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Farm Pond System for the Town of Oak Bluffs. 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. Nitrogen loads from the watershed (by sub-watershed) surrounding the estuary were derived from the Martha's Vineyard Commission land-use database. In addition, nitrogen input parameters to the water quality model are described (Section IV). 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). Results of hydrodynamic modeling of tidal exchange is presented in Section V. Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities). Site specific nitrogen and salinity levels within the estuary and in inflowing waters were used to validate the water quality model, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section

VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of the component sub-embayments was performed that included a review of existing water quality information and the results of a benthic analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of the Pond in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration of the Pond. This latter assessment represents only one of many solutions and is produced to assist the Towns in developing a variety of alternative nitrogen management options for this system. Finally, analyses of the Farm Pond System were undertaken relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and examine inlet widening to improve nitrogen related water quality. The results of the nitrogen modeling for each scenario have been presented in Section VIII.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

In most marine and estuarine systems, such as the Farm Pond System, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. As a result, there has been significant effort to develop tools for predicting how modification of watershed nitrogen loads and changes in tidal flushing quantitatively cause changes in the concentrations of water column nitrogen in the receiving estuary. Further development of these approaches 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. In contrast, some approaches can be tailored for each individual estuary of interest, but require large amounts of site-specific information and therefore are not generally applied. The present Massachusetts Estuaries Project (MEP) effort uses one such site-specific approach. The assessment 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 within individual estuaries. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for the specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Farm Pond System. As the MEP approach requires substantial amounts of site-specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of “data mining” and to gather additional information on an estuary’s habitat quality and unique features.

A number of studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Farm Pond System over the past decade which helped to inform the MEP process. As the primary stakeholder to the Farm Pond system, the Town of Oak Bluffs, in collaboration with the Martha’s Vineyard Commission (MVC), has been among the first communities to become concerned over perceived degradation of its coastal embayments. The importance of this system to the citizens of Oak Bluffs can be seen in the formation in 2005 of a citizen stewardship group, The Friends of Farm Pond who have been active in promoting restoration of this estuary. A review of the history of Farm Pond and recent efforts to preserve it is presented in an article by Tom Dunlop "Saving Farm Pond" published in the Martha's Vineyard Magazine, September - October: 29-37, 2004. Stewardship of estuaries within the Commonwealth depends upon citizens groups, like the Friends of Farm Pond, working with the Towns and regional agencies, like the MVC, to move the planning and implementation of estuarine management alternatives forward.

To address local concerns relating to changes in habitat quality of the Farm Pond System and the effects of shoreline retreat on the system or its tidal exchange several studies were conducted in the past, such as: 1) "Harthaven Inlet Study: Evaluation and Recommendations" by Joseph Forns (1983) which discussed shoaling problems associated with the tidal inlet due to coastal processes and some recommendations for dredging, modifying jetties, dune restoration and increasing the size of the culvert (inlet) to enhance tidal exchange were presented; 2) "Report on the Hydrology and Water Quality Characteristics of Farm Pond, Oak Bluffs, Martha's Vineyard, Massachusetts prepared by IEP, Inc., Sandwich, MA for the Oak Bluffs Board of Health (1988), primarily as a result of high indicator bacteria levels within the pond and consequent restrictions on shellfish harvest; 3) "Final Environmental Impact Report, Farm Pond, Oak Bluffs, Martha's Vineyard, Massachusetts" (1991) prepared by IEP following on the 1988 study. The focus was to increase tidal exchange within Farm Pond by installing a new culvert (71" x 47"). A smaller 47 inch diameter round culvert was what was actually installed.

Directly supporting the present Massachusetts Estuaries Project effort to develop a nitrogen threshold for Farm Pond are three key investigations which relate directly to assessing nutrient related water quality. These studies provided quantitative information on water column parameters over multiple summers (including nitrogen), surveys of eelgrass distribution and quantitative hydrodynamic analysis of various tidal inlet configurations. These studies are summarized below.

Farm Pond Nutrient Related Water Quality Monitoring: The Martha's Vineyard Commission has worked with Martha's Vineyard towns to collaboratively monitor the nutrient related water quality (as opposed to bacteria) of the estuaries across the island. Farm Pond is one of those systems. Summertime monitoring of the water quality in Farm Pond began in 2003 and continued at a high level through 2006 and with some samples collected in 2007. After a hiatus in 2008, full sampling resumed in 2009. On average 18 summer sampling events were completed for each of the stations in Farm Pond for the period 2003-2009 (Figure II-1). The monitoring undertaken was a collaborative effort with the MVC (Bill Wilcox) coordinating the field effort and chemical assays being completed by the SMAST Coastal Systems Analytical Facility. The Coastal Systems Analytical Facility is located in the School for Marine Science and Technology UMASS-Dartmouth, 706 S. Rodney French Blvd, New Bedford, MA, and the laboratory Points of Contact are Sara Sampieri 508-910-6325 (ssampieri@umassd.edu) or Mike Bartlett (mbartlett@umassd.edu). Use of the SMAST Analytical Facility ensured sufficient sensitivity and accuracy of the analytical protocols and that proper QA/QC procedures were followed to allow incorporation of the data into the MEP analysis. The focus of the Farm Pond effort has been to gather site-specific data on the current nitrogen related water quality throughout its estuarine reach to support assessments of habitat health. This baseline water quality data are a prerequisite to entry into the MEP. Implementation of the MEP's Linked Watershed-Embayment Approach necessarily incorporates the quantitative water column nitrogen data (2003-2009) gathered by the Monitoring Program and watershed and embayment data collected by MEP staff.

Farm Pond Eelgrass Distribution: Distribution of eelgrass beds is a fundamental part of determining the nitrogen threshold for estuaries in southeastern Massachusetts. Uncertainty is greatly reduced if there is a time-series of maps and the maps are field verified. For Farm Pond the only suitable eelgrass distribution data were generated by Martha's Vineyard Commission working with the Town of Oak Bluffs (1997 and 2006 maps) and field surveys by SMAST scientists through the MEP (2006).

A survey of the eelgrass beds of Sengekontacket and Farm Ponds in Edgartown and Oak Bluffs, Massachusetts was conducted by Kara Hempy (UMass Intern) and William Wilcox (MVC Water Resource Planner). This study was funded by the Massachusetts Department of Environmental Management Lakes and Ponds Program and the Martha's Vineyard Commission under the auspices of the Oak Bluffs Conservation Commission. This effort was to map the macrophyte beds, primarily eelgrass (Zostera marina) of Farm and Sengekontacket. The study was completed over a 10 week period during June through August of 1997 by direct visual inspection along 28 transects by SCUBA divers and by boat. At the time of the 1997 survey, the 39 acre Farm Pond had tidal exchange with Vineyard Sound through a culvert under Beach Road. Farm Pond had a mean depth of less than 1 meter (about 2.5 feet) during the survey period. This study of eelgrass presence and distribution in Farm Pond was intended to serve as a baseline to evaluate the eelgrass beds in the future. In addition, the status of the health and productivity of the beds were evaluated and a trial eelgrass transplanting was carried out in Sengekontacket Pond, with the goal of determining the potential for eelgrass restoration in the future. An additional survey of Farm Pond was conducted in 2006 again by the MVC and Town of Oak Bluffs, with independent survey validation by SMAST MEP Technical Team scientists. True to its intended purpose, the eelgrass mapping of Farm Pond in 1997 was used as the benchmark for determining changes in eelgrass distribution in the MEP analysis.

Farm Pond Hydrodynamic Analysis Present Barrier: Among the historical studies completed on Farm Pond was a detailed analysis of present hydrodynamics and alternative inlet analysis prepared by Applied Coastal Research and Engineering, Inc. (ACRE) for Massachusetts Coastal Zone Management (2006). Included in this effort by ACRE engineers (also members of the MEP Technical Team) was a hydrodynamic analysis of circulation in Farm Pond.

The hydrodynamic study of Farm Pond consisted of field measurements of bathymetry and tide stage recording to characterize the physical system, construction of a site-specific numerical hydrodynamic model of Farm Pond and modeling hydrodynamic effects of alternative inlet designs. The field surveys addressed the lack of adequate bathymetry data for this basin. Tides were recorded in the Pond and in Vineyard Sound for 34 days using autonomous instrumentation. Both the bathymetric and tidal data are necessary to run and calibrate the hydrodynamic model for Farm Pond. Development of a numerical hydrodynamic model of Farm Pond used the bathymetry survey data and a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data from Vineyard Sound were used to define the open boundary condition that drives circulation, and data measured within the system were used to calibrate and verify model performance to ensure that it accurately represented the dynamics of the real, physical system. Finally, the calibrated hydrodynamic model of Farm pond was used to perform an evaluation of a range of possible inlet modifications, in order to assess relative flushing performance of each modeled scenario over present conditions. A particle tracking model was employed to further quantify the differences of each modeled scenario. The modeling and analysis of inlet modification alternatives for enhancing flushing and circulation directly supports the present MEP assessment and ultimately formed the basis of the Massachusetts Estuaries Project numerical modeling effort in the Farm Pond system.

Since the initial results of the Water Quality Monitoring Program (2003-2005) and the above studies indicate that portions of the Farm Pond system are presently impaired by the combination of land-derived nitrogen inputs and restricted tidal exchange, the Town of Oak Bluffs and the Martha's Vineyard Commission (MVC) undertook participation in the Massachusetts Estuaries Project to complete ecological assessment and water quality modeling for the development of nutrient thresholds for restoration of Farm Pond.

Regulatory Assessments of Farm Pond Resources - In addition to locally generated studies, Farm Pond is part of the Commonwealth's environmental surveys to support regulatory needs. The Farm Pond Estuary contains a variety of natural resources of value to the citizens of Oak Bluffs as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP also gathers the available information on these resources as part of its assessment, and presents some of them here for reference by those providing stewardship for this estuary and some in Chapter 7 to support the nitrogen thresholds analysis. For the Farm Pond Estuary these include:

- Designated Shellfish Growing Area – MassDMF (Figure II-2)
- Shellfish Suitability Areas – MassDMF (Figure II-3)
- Anadromous Fish Runs - MassDMF (Figure II-4)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-5)

The MEP effort builds upon earlier watershed delineation and land-use analyses, the hydrodynamic modeling, historical eelgrass surveys and water quality surveys discussed above. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Farm Pond Estuarine System. The MEP has incorporated all appropriate data from pertinent previous studies to enhance the determination of nitrogen thresholds for the Farm Pond System and to reduce costs to the Town of Oak Bluffs.

Figure II-1. Town of Oak Bluffs/MV Commission Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the Town, MV Commission and SMAST staff during summers 2003-2009.

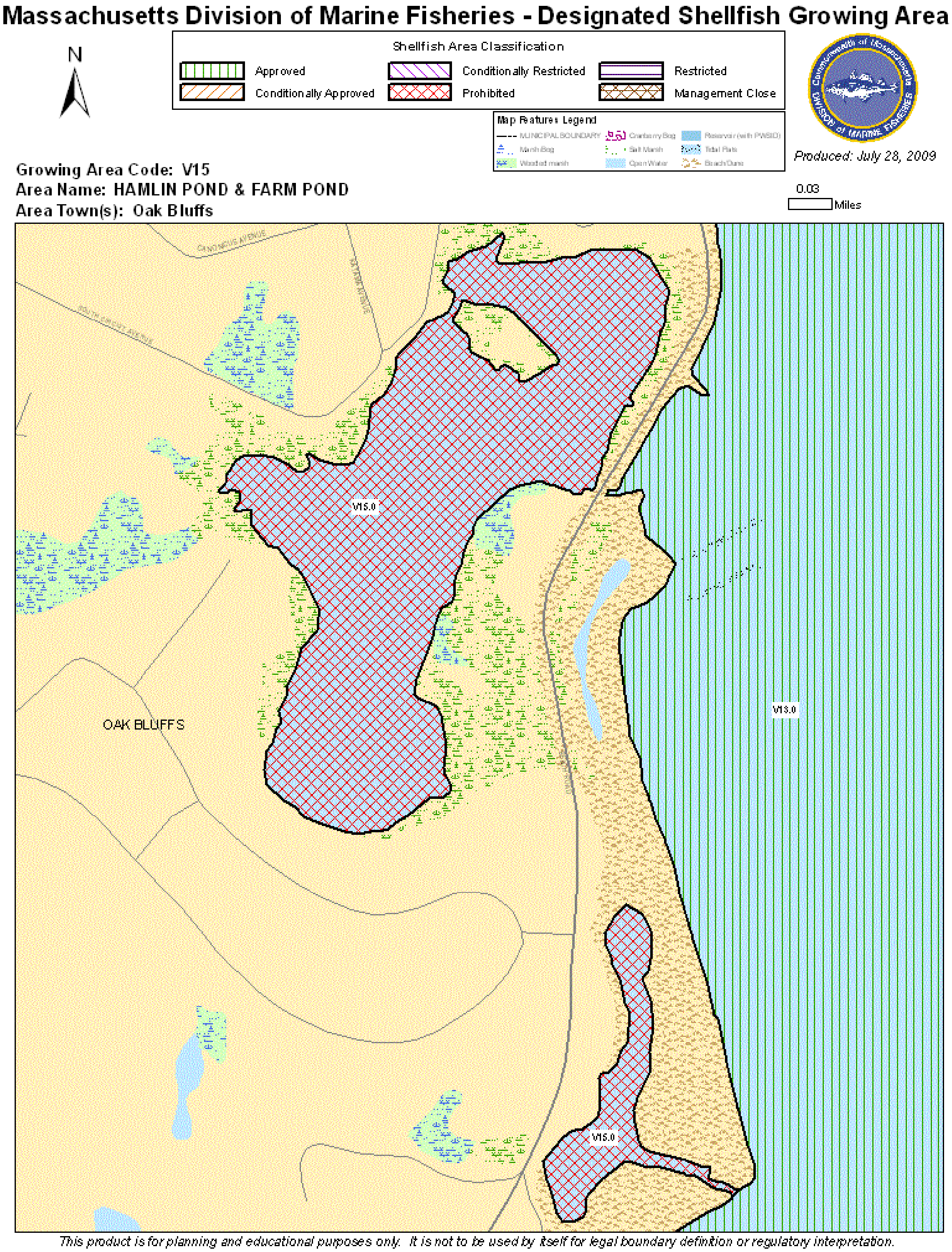


Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

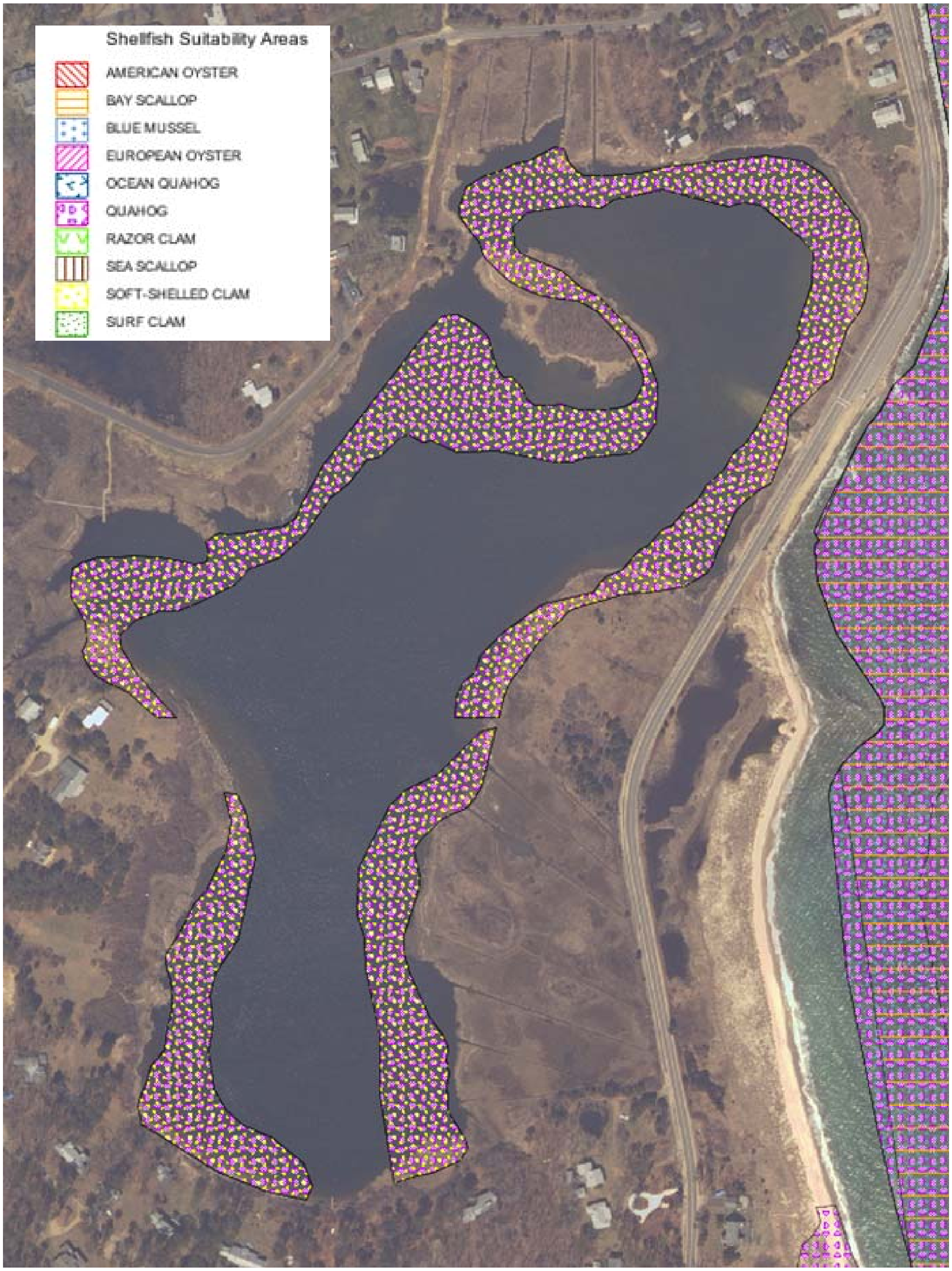


Figure II-3. Location of shellfish suitability areas within the Farm Pond Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

Figure II-4. Anadromous fish runs within the Farm Pond Estuary as determined by Mass Division of Marine Fisheries. The red diamonds show areas where fish were observed.

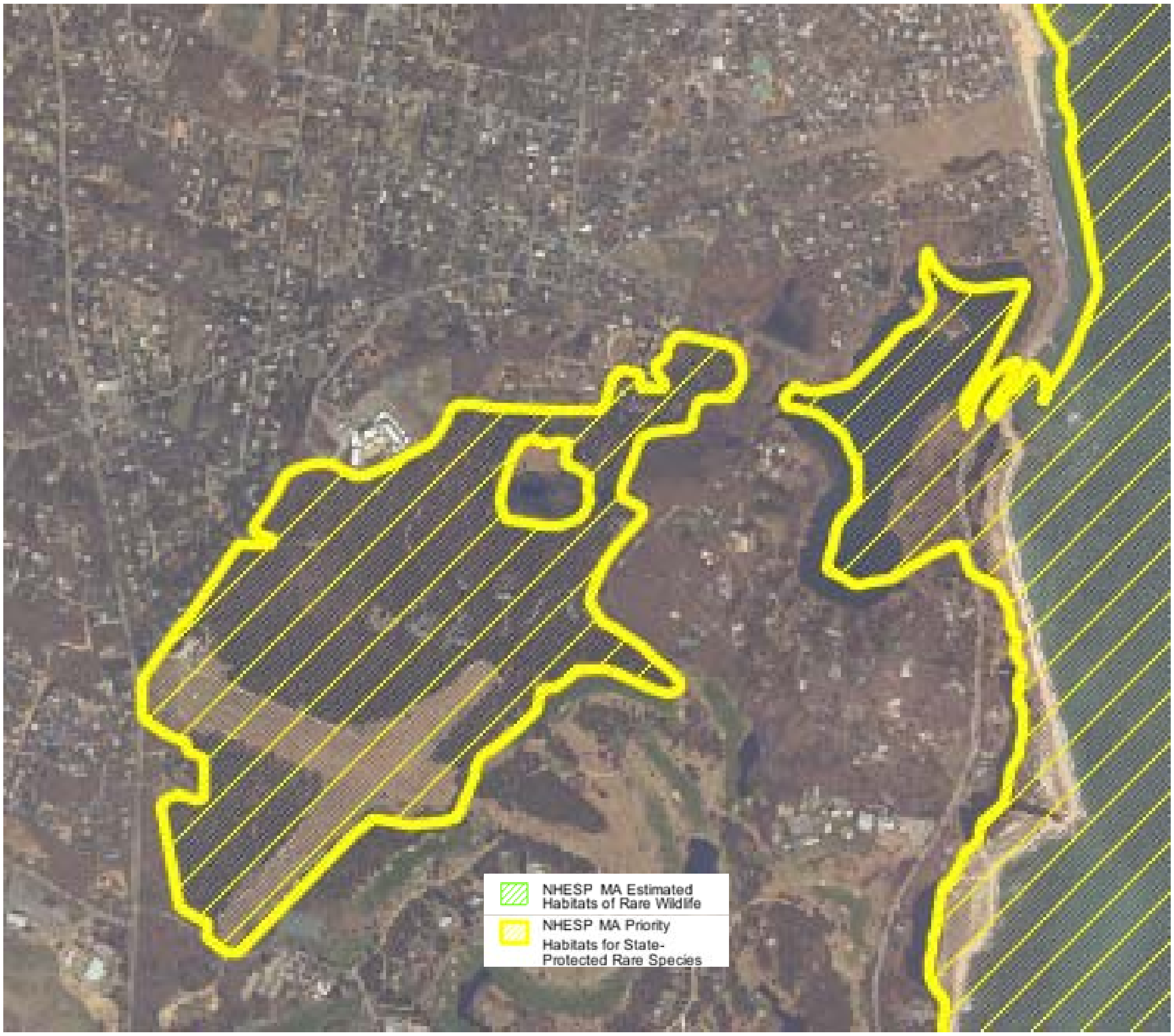


Figure II-5. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Farm Pond Estuary as determined by - NHESP.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

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

Farm Pond is a 42 acre coastal salt pond at high water which includes approximately 8 acres of salt marsh. The Pond was derived from the old de Bettencourt Farm that once occupied its shores (Dunlop 2004). The pond is characterized by a single main basin with a small connected upper basin partially separated by an undeveloped island, Woody Island, which was detached from the upland by an artificial channel. The watershed to Farm Pond is completely sited within the Nantucket Moraine sediments consisting mainly of clay, sand, gravel and glacial till overlain by drift (Woodworth and Wigglesworth 1934). These sediments were deposited as the ice sheets retreated at the end of the last glacial period. Since the retreat of the ice, the deposits along the shore have been reworked by the ocean forming the beach and barrier beach deposits. The relatively porous sediments within the Farm Pond watershed create a hydrologic environment nearly completely lacking streams where the watershed boundary is defined by elevation of the groundwater and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). Freshwater discharge to estuaries is usually composed of surface water inflow from streams, which receive much of their water from groundwater base flow, and direct groundwater discharge. For a given estuary, differentiating between these two water inputs and tracking the sources of nitrogen that they carry requires determination of the portion of the watershed that contributes directly to a stream and the portion of the groundwater system that discharges directly into an estuary as groundwater seepage. In the Farm Pond watershed, virtually all freshwater from the watershed enters the estuary as groundwater.

The watershed and groundwater system to Farm Pond, within the eastern moraine deposits, has generally been characterized as approximately as permeable as the outwash plain and the 1977 United States Geological Survey (USGS) regional water table map shows northern groundwater flow lines from the western moraine toward the eastern coast that seem uninfluenced by the moraine (Delaney, 1980). In 1991, the USGS developed another regional water table map, which generally showed the same water table contours (Masterson and Barlow, 1996). Masterson and Barlow constructed a regional two-dimensional, finite-difference flow model that could be used to calculate drawdowns in groundwater levels due to pumping of public water supply wells, but could not be calibrated against actual water level readings. These USGS characterizations of the geology, including the installation of numerous long-term monitoring wells, over the last few decades have provided the basis for other activities, including the delineation of the watersheds to the Vineyard's estuaries.

In 1994, Whitman and Howard Inc. produced a groundwater model with a domain that covered Martha's Vineyard eastern moraine and the outwash plain; this model was based on the publicly available USGS MODFLOW three-dimensional, finite difference groundwater model code. In 1999, Earth Tech updated the 1994 Whitman and Howard regional model and used an associated model to delineate watersheds. These watersheds were adopted by the Martha's Vineyard Commission (MVC) and are used in the MVC's guidance for the review of Developments of Regional Impact and direction to the towns of the Martha's Vineyard.

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

III.2 FARM POND CONTRIBUTORY AREAS

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

MEP technical staff revised the model grid to match orthophotographs of the island, which resulted in a model grid with 126 rows oriented southwest and 167 columns oriented southeast. Hydraulic conductivities were reworked to match the revised grid. Outputs from the revised model were compared with water table elevations generated for previously MassDEP-approved Zone II drinking water well contributing area delineations and the match was acceptable. This delineation was further enhanced by the incorporation of groundwater mounding information associated with discharge at Ocean Park from the Oak Bluffs Wastewater Treatment Facility at Ocean Park. Modeling and field tests in the area established that the mound is sustained throughout the year (Horsley Witten & Wright Pierce, 1997). Technical staff then used the groundwater model and the Ocean Park mounding to define the watershed and contributing areas to Farm Pond and its subestuaries. The Farm Pond watershed is situated along the eastern edge of Martha's Vineyard and is bounded by the Atlantic Ocean/Nantucket Sound to the east (Figure III-1).

MEP staff utilized the Farm Pond watershed to develop daily discharge volumes for the two sub-watersheds as calculated from the watershed areas and an island-specific recharge rate. In order to develop the groundwater discharge volumes, MEP staff determined a recharge rate of 28.7 inches per year for Martha's Vineyard. This recharge rate estimate was largely based on review of the relationship between recharge and precipitation rates used on Cape Cod. In the preparation of the Cape Cod groundwater models, the USGS used a recharge rate of 27.25 in/yr for calibration of the groundwater models to match measured water levels (Walter and Whealan, 2005). The Cape Cod recharge rate is 61% of the estimated 44.5 in/yr of precipitation on the Cape. Precipitation data collected by the National Weather Service at Edgartown since 1947 has an average over the last 20 years of 46.9 in/yr (http://www.mass.gov/dcr/waterSupply/rainfall/precipdb.htm). If the Cape Cod relationship between precipitation and recharge is applied to the average Martha's Vineyard precipitation rate, the estimated recharge rate on Martha's Vineyard is 28.7 in/yr. This rate was used to estimate groundwater flow to Farm Pond and its two subwatersheds (Table III-1). The discharge volumes developed for the subwatersheds were used to support the salinity calibration of the tidal hydrodynamic models. The overall estimated groundwater flow into Farm Pond from the MEP delineated watershed is 3,249 m3/d.

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

Watershed	Watershed #	Watershed Area (acres)	Discharge	
			m^3/day	ft^3/day
Farm Pond	1	353	2,856	100,858
Ocean Park	2	49	393	13,862
TOTAL		402	3,249	114,721

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

The watershed delineation in this report appears to be the first watershed delineation based on groundwater information for Farm Pond. Given the model grid refinements completed by the MEP Technical Team, led in this effort by USGS staff, MEP Technical Team staff are confident that the delineation for Farm Pond (Figure III-1) is both accurate and an appropriate basis for implementation of the linked watershed-embayment modeling approach.

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

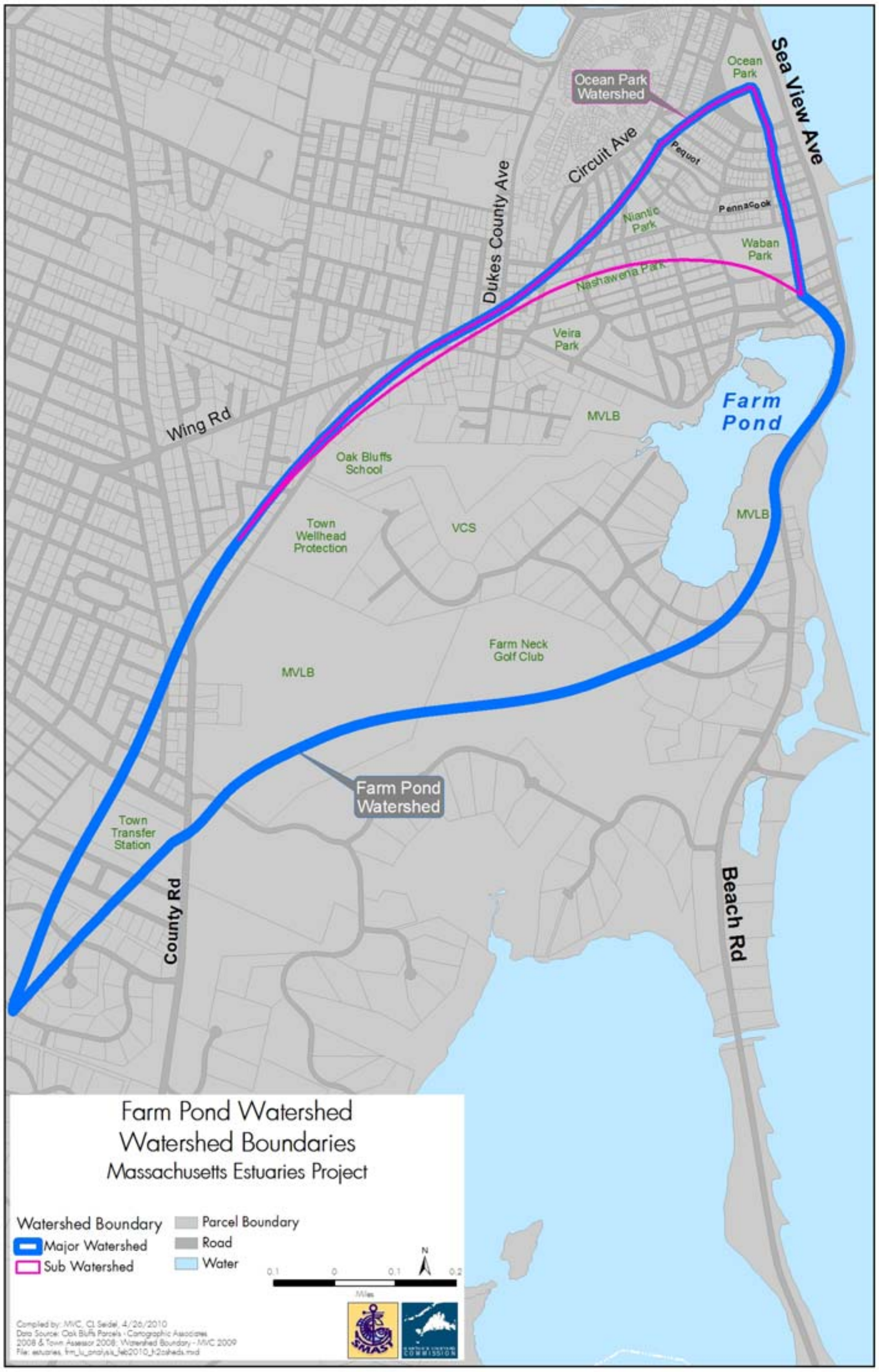


Figure III-1. Watershed and sub-watershed delineations for the Farm Pond estuary system. Sub-watersheds to embayments are based upon watershed features, such as ponds or rivers, and functional estuarine sub-units in the water quality model (see section VI).

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

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

The MEP Technical Team worked with the Martha's Vineyard Commission (MVC) staff to develop the watershed nitrogen loads to the Farm Pond estuary. This effort led to the identification of watershed nitrogen sources and the development of nitrogen-loading rates (Section IV.1) from the watershed to the tidal waters of Farm Pond (Section III). The Farm Pond watershed is relatively small and is comprised of two sub-watersheds; one to the main portion of Farm Pond and another created by the discharge of treated wastewater from the Oak Bluffs Wastewater Treatment Facility at Ocean Park (see Chapter III).

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. Loading from land-uses also required individual lot-by-lot data and were also derived from other in-depth studies for different portions of the watershed. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Module based upon sub-watershed-specific land uses and associated nitrogen loading rates. For the Farm Pond System, MVC supplied land-use data were transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as water use data provided by the Oak Bluffs Water District and nitrogen discharge from the Oak Bluffs Wastewater Facility). The resulting nitrogen loads represent the "potential" or unattenuated nitrogen loading to the receiving estuarine waters, since attenuation during transport through streams or freshwater ponds has not yet been included.

Natural attenuation of watershed nitrogen during stream transport or in passage through fresh ponds of sufficient size to affect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. However, the watershed to Farm Pond contains only surface fresh water features that are too small for delineation of separate watersheds, thus they are not explicitly included in the watershed analysis. There are no significant streams discharging to Farm Pond. If unaccounted small features were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly overestimated given the distribution of nitrogen sources relative to these small features within the watershed. Based upon these considerations, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the two sub-watersheds that directly discharge groundwater to the estuary.

Internal nitrogen recycling from the estuary sediments was also determined throughout the tidal reach of the Farm Pond Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Modeling Approach (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

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

Figure IV-1 shows the land uses within the Farm Pond watershed. Land uses in the study area are grouped into eight land use categories: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) undeveloped (including residential open space), 6) public service/government, including road rights-of-way, and 7) golf courses. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2008). "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (e.g., wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges.

In the overall Farm Pond watershed, the predominant land use based on area is public service (government owned lands, roads, and rights-of-way), which accounts for 47% of the overall watershed area; residential is the second highest percentage of the system watershed (32%) (Figure IV-2). Public service land uses are also the dominant land use category based on area in both individual sub-watersheds. However, on a number of parcel basis, residential parcels predominate accounting for 79% of the total number of parcels in the watershed. Of the residential land-use, single-family residences (MADOR land use code 101) account for almost all parcels (90%) and area of residential land-use (86%). Undeveloped parcels are the third highest land use classification on an area basis within the overall watershed, although only 2% of the Ocean Park sub-watershed is undeveloped compared to 14% of the larger Farm Pond sub-watershed. Overall, undeveloped land uses account for 13% of the entire Farm Pond watershed area, while golf course properties account for the next highest percentage (7%) following public service, residential, and undeveloped areas.

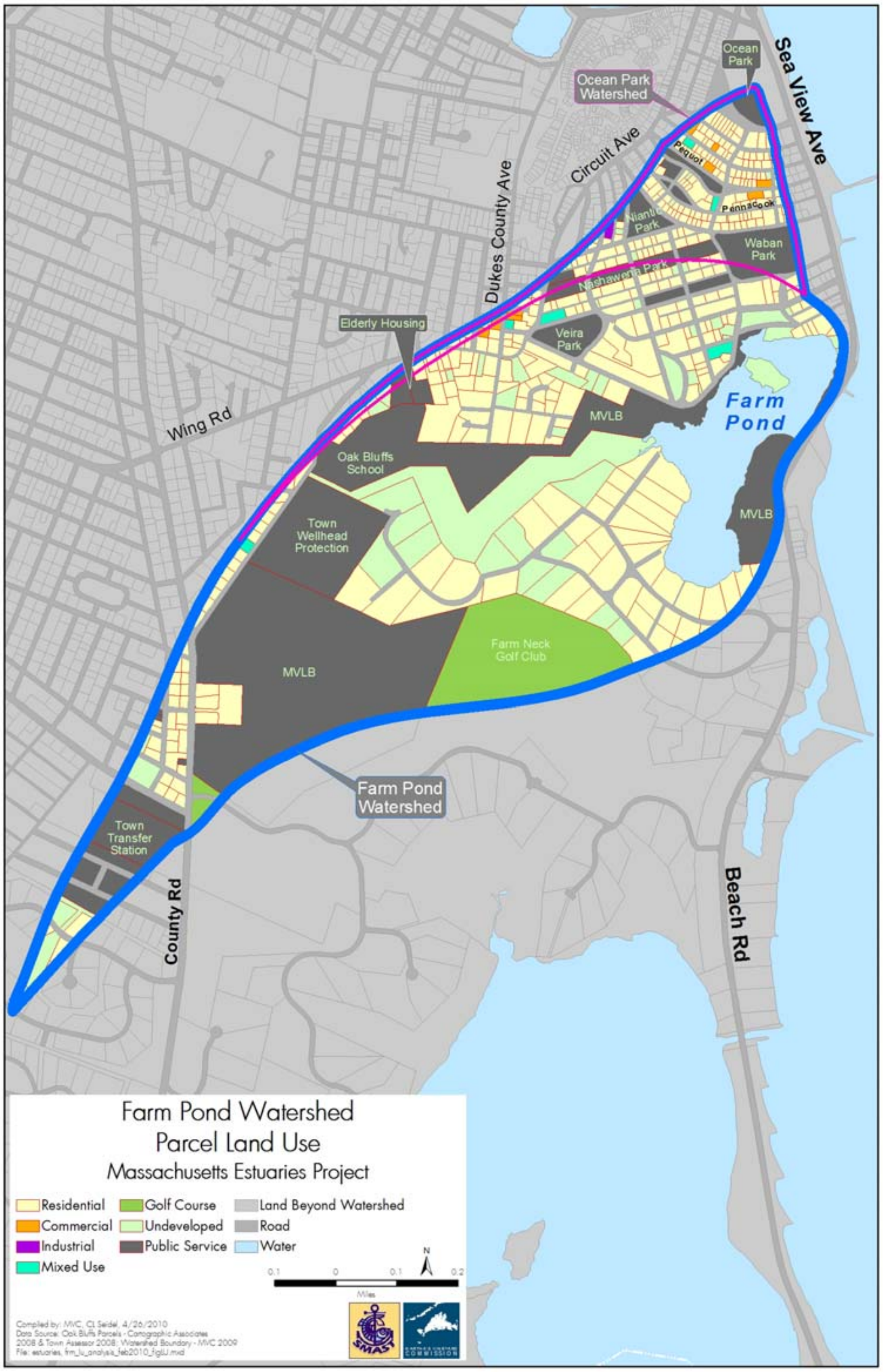


Figure IV-1. Land-use in the Farm Pond watershed. The estuary and its watershed are completely within the Town of Oak Bluffs. Land use classifications are based on assessors' records provided by the town.

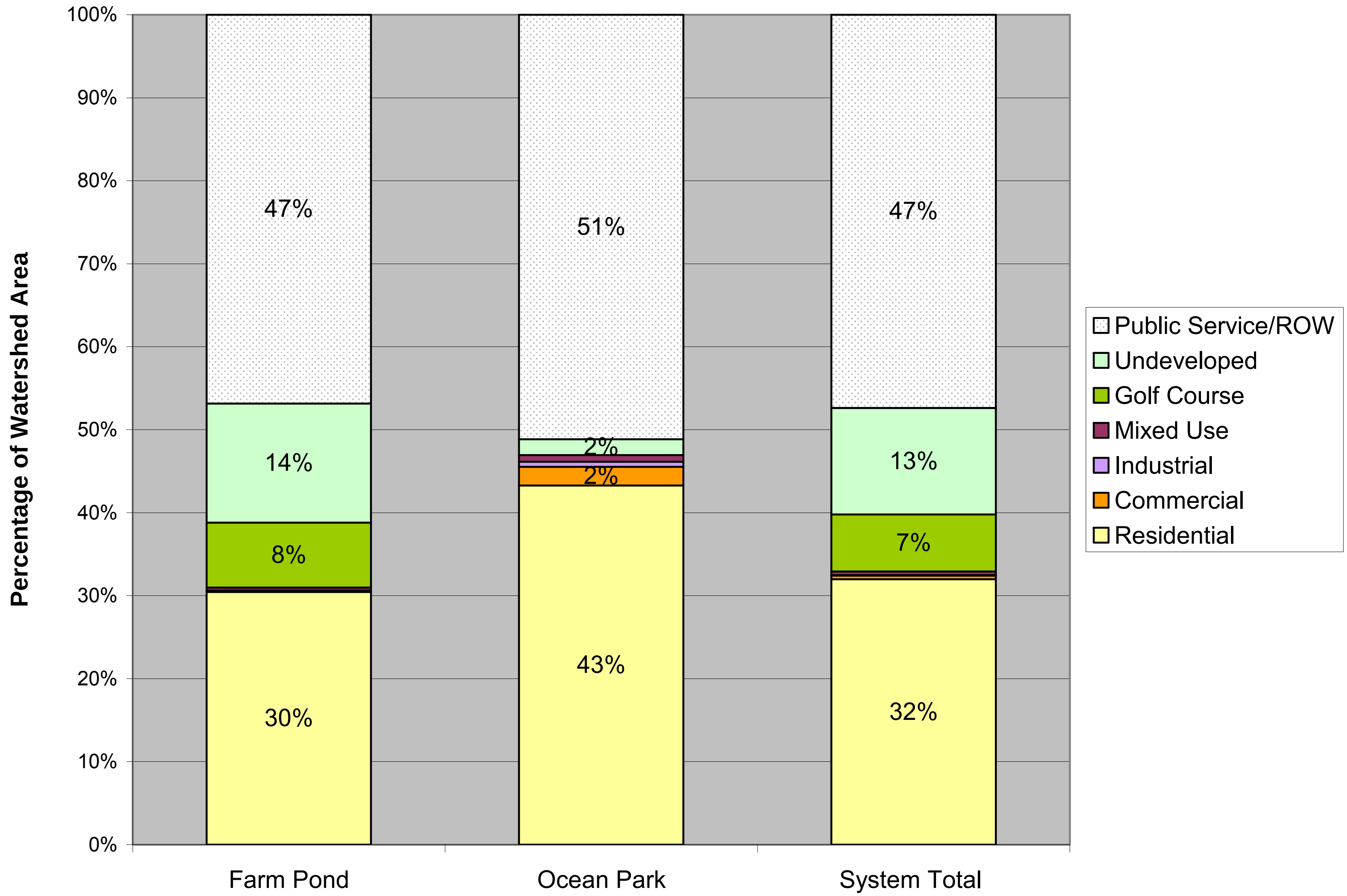


Figure IV-2. Distribution of land-uses within the 2 sub-watersheds and the entire watershed to Farm Pond. Land use categories are generally based on assessor's land use grouping recommended by MADOR (2008). Only percentages greater than or equal to 2% are shown.

In order to estimate wastewater flows, MEP staff generally work with municipal or water suppliers operating within the watershed contributing to the estuary under assessment. Parcel-by-parcel water-use data are sought as the best determinant of wastewater generation from each parcel (after correcting for consumptive uses). MVC staff contacted the Oak Bluffs Water District (OBWD) who generously provided average water use information for properties within and near the Farm Pond watershed. MVC Staff reviewed four years of water use records (2003-2006) for approximately 464 accounts. This review found the average parcel with an account used 56,144 gallons per year with a range of zero use to 34,593 gallons per day. This average water use translates into 154 gallons per day per account compared to the town-wide average of 160 gallons per day. MEP and MVC staff used a town-wide average of 160 gallons per day as a proxy for wastewater generation from septic systems on all developed properties without water use accounts in the Farm Pond watershed. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the average water-use, nitrogen concentration, and consumptive loss of water prior to discharge to the septic system (see Section IV.1.2).

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts, decennial census data yields accurate estimates of total population only in selected watersheds. To correct for this uncertainty and more accurately assess current nitrogen loads, the MEP employs a water-use approach. The water-use approach is generally applied on a parcel-by-parcel basis within a watershed, where annual water meter data are linked to assessors parcel information using GIS techniques. The parcel specific water use data are 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 have limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water used based on average residential occupancy to measured average water uses. This is performed as a quality assurance check to increase certainty in the final results. This comparison has shown that the larger the watershed the better the match between average water use and occupancy. For example, in the cases of the combined Great Pond, Green Pond and Bournes Pond watershed in the Town of Falmouth and the Popponesset Bay/Eastern Waquoit Bay watershed, which cover large areas and have significant year-round populations, the septic nitrogen loading based upon the census data are within 5% of that from the water use approach. This comparison matches some of the variability seen in census data itself. Census blocks, which are generally smaller areas of any given town, have shown up to a 13% difference in average occupancy from town-wide occupancy rates. These analyses provide additional support for the use of the water use approach in the MEP study region.

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

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

In order to provide an independent validation of the average residential water use within the Farm Pond System watershed, MEP staff reviewed US Census population values for the Town of Oak Bluffs. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. Based on data collected during the 2000 US Census, average occupancy within Oak Bluffs is 2.34 people per occupied housing unit with 42% year-round occupancy of available housing units. Average water use for single-family residences with municipal water accounts in the Oak Bluffs MEP study area is 137 gpd. This flow closes matches estimated wastewater estimate derived by multiplying the state Title 5 estimate of 55 gpd per capita by the average Oak Bluffs occupancy from the 2000 US Census (128 gpd). Multiplying the average measured water use by 0.9 to account for consumptive use results in a study area average wastewater flow (septic system) per single-family residence of 123 gpd.

The Census-based estimate does not account for the estimated population increase associated with summer visitors to Martha's Vineyard. Estimates of summer populations on Cape Cod and the Islands derived from a number of approaches (*e.g.*, traffic counts, garbage generation, WWTF flows) generally suggest average population increases from two to three times year-round residential populations measured by the US Census. If it is assumed that seasonal properties, 58% of the residential units according to the 2000 Census, are occupied at twice the year-round occupancy for three months, the estimated annualized average town-wide water use would be 161 gpd, while if the seasonal properties are occupied at three times the year-round occupancy for three months, the estimated average water use would be 193 gpd. Given that the average wastewater generation for all water use accounts in the study area is within this range, this analysis suggests that the average water use can be used to determine average wastewater estimates. It should be emphasized that measured water use is used as the basis for the MEP wastewater flows to avoid the necessary assumptions of seasonal occupancy rates as described above.

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

Water use information exists for 98% of the developed parcels that are not connected to the sewer system in the Farm Pond watershed. Parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (*e.g.*, 101 or 325), have been confirmed as having buildings on them through a review of aerial photographs, and/or do not have a listed account in the water use databases. Of the 10 developed parcels without water use accounts, 7 (70%) are classified as single-family residences (land use code 101). These parcels are assumed to utilize private wells and were assigned the Oak Bluffs study area average water use for single-family residences of 137 gpd in the watershed nitrogen loading modules. Other developed properties assumed to utilize private wells were assigned the average flow from properties with the same land use code.

Oak Bluffs Wastewater Treatment Facility

The Town of Oak Bluffs maintains a municipal wastewater treatment facility (WWTF) with subsurface effluent discharge fields under Ocean Park (see Figure IV-1). The WWTF treats wastewater from a sewer collection system generally concentrated in the mostly densely developed portions of town. MEP and MVC staff obtained three years (2007-2009) worth of WWTF effluent flow and total nitrogen discharge information. Staff also reviewed previous evaluations of the WWTF discharge, including Horsley Witten & Wright Pierce (1997). This information was used to review the current and historic nitrogen loading from the WWTF.

According to the available monitoring data, the Oak Bluffs WWTF produced annual wastewater flows of 28, 27, and 33 million gallons in 2007, 2008, and 2009, respectively. These flows followed a consistent yearly cycle with monthly flows of 0.8 to 1.5 million gallons in January through March followed by increasing flows peaking in July and August of approximately 5 to 6 million gallons per month (Figure IV-3). The only slight difference in flows between the years is an increasing trend over the three years in the “shoulder” months bordering the summer period of peak flow.

Average monthly total nitrogen concentrations for the WWTF generally fluctuate within a fairly constrained range between 3 and 5 ppm. The maximum concentration over the three years between 2007 and 2009 is 5.2 ppm, while the minimum is 2.95 ppm. Over the three years higher concentrations are generally measured in the winter months and during the peak flows of summer. Given these measured flows and total nitrogen concentrations, the nitrogen loads from the WWTF are fairly consistent over the three years between 2007 and 2009 with loads of 448, 511, and 532 kg, respectively (see Figure IV-3). For the purposes of the MEP assessment of Farm Pond, project staff averaged the load from 2008 and 2009.

Discharge of treated effluent to the aquifer at Ocean Park has created a permanent groundwater mound. MVC staff review of available groundwater modeling and large scale slug tests at Ocean Park (HW & WP, 1997) indicate that the mound diminishes, but is sustained, during winter months. Consequently, effluent discharged at Ocean Park flows radially from this mound and modifies the groundwater-based watershed to Farm Pond (see Chapter III). MVC staff have estimated that a quarter of the mound and, therefore, a quarter of the discharged effluent flows to Farm Pond. For the purposes of the MEP assessment of Farm Pond the discharge from the Oak Bluffs WWTF results in an annual load of 132 kg of nitrogen to Farm Pond. However, this WWTF load is more than offset by present sewering within the Farm Pond watershed. According to the water accounts, there are 142 parcels within the Farm Pond watershed that are connected to the WWTF collection system. These parcels are 24% of all the parcels in the shed and their collective average flow is 7.4 million gallons over the four years worth of water use data. This average flow is approximately 22% of the total effluent flow from the WWTF in 2009.

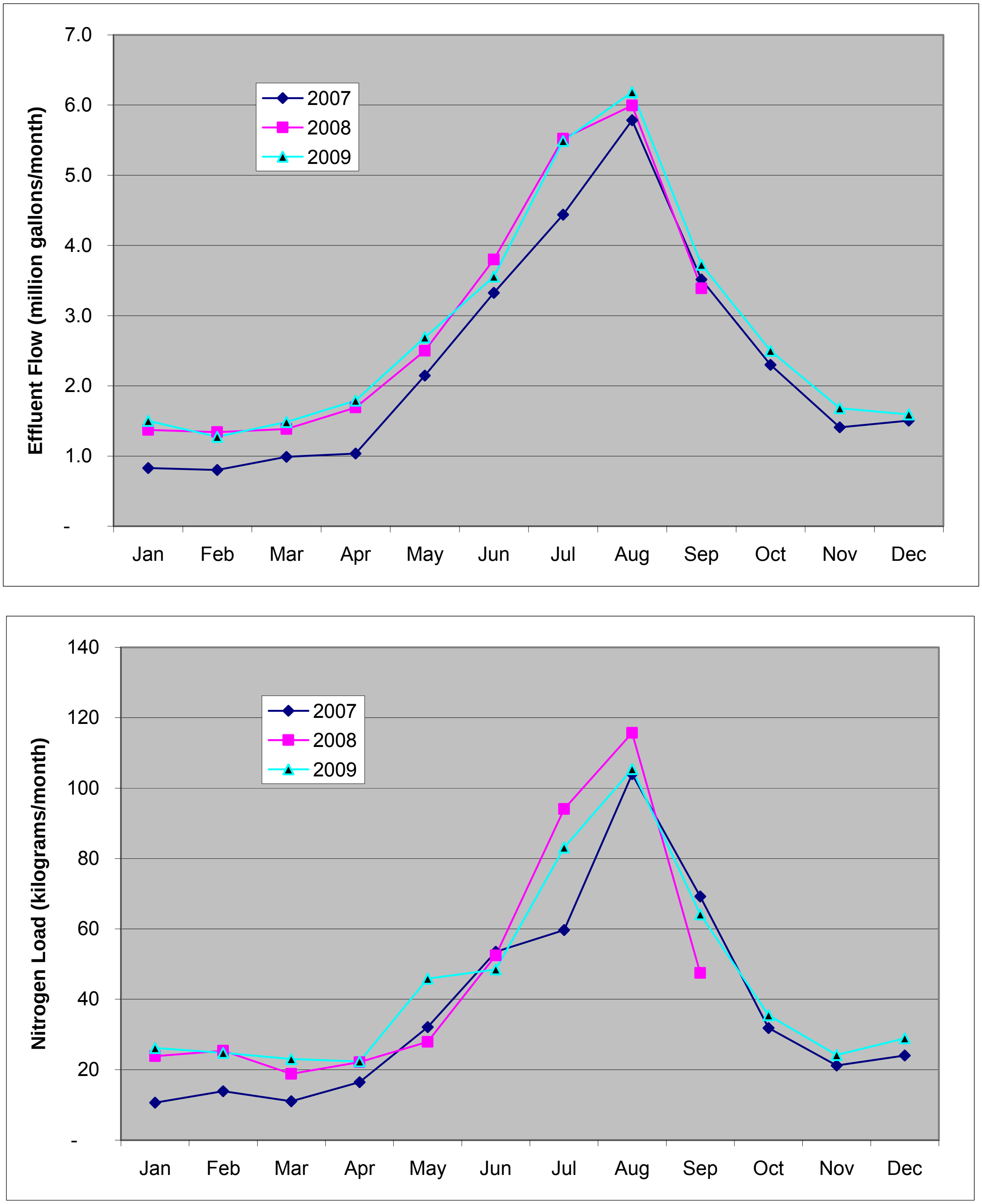


Figure IV-3. Effluent flow and total nitrogen-loading data from Town of Oak Bluffs Wastewater Treatment Facility (2007-09).

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and cranberry bogs, with residential lawns being the predominant source within this category. In order to add all of these sources to the nitrogen-loading model for the Farm Pond system, MVC staff under the guidance of MEP staff reviewed available information about residential lawn fertilizing practices and obtained information on fertilizer application rates at the Farm Neck Golf Club. No cranberry bogs or other farmland were identified within the watershed.

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

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. The assessment accounted for proximity to fresh ponds and embayments. Based upon ~300 interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sq. ft., 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a leaching rate of 20% results in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors are generally used in the MEP nitrogen loading calculations. The MEP fertilizer leaching rate of 20% recently received a detailed review prepared by Horsley Witten Group Inc. The task was to independently determine a nitrogen fertilizer leaching rate from turf grass specific to the permeable soils typical of the watersheds to southeastern Massachusetts estuaries, and then compare it to the MEP analysis. The analysis used both the results of previous studies and new data collected subsequent to the initiation of the MEP. The results indicated a leaching rate of 19% and the study concluded that "the MEP leaching rate estimate of 20% is reasonable (Horsley Witten Group, 2009).

In 1999, a land use survey on Martha's Vineyard reviewed lawn sizes, including portions of the Farm Pond watershed (MV Commission, 1999). This survey found that within the Farm Pond watershed the average lawn size was 1,820 square feet, while within the Ocean Park subwatershed, where parcels are smaller, that the average lawn size was only 400 square feet. This same survey found that average household fertilizer application rates averaged 1 lb N per 1,000 square feet of residential lawn. MEP Technical staff reviewed these factors with MVC staff and included these factors in the development of the Farm Pond watershed nitrogen-loading model. MVC staff also determined individual lawn size on selected larger parcels and the area of selected ballfields based on review of aerial photographs; these site-specific areas were also included in the watershed loading model. Other factors in the model are those generally used in MEP nitrogen loading calculations.

Portions of the Farm Neck Golf Club are also located within the Farm Pond watershed. MVC staff were unsuccessful in obtaining site-specific fertilizer application rates for the Club, so the average nitrogen application rates from 14 golf courses previously supplied to MEP staff during other estuary assessments were used to estimate the nitrogen load from the Farm Neck Golf Club. These average nitrogen application rates are as follows: greens, 3.8 pounds per 1,000 sq. ft; tees, 3.5 pounds per 1,000 sq. ft; fairways 3.3 pounds per 1,000 sq. ft., and roughs, 2.5 pounds per 1,000 sq. ft. The area of the greens, tees, fairways, and roughs of the Club were determined from a review of aerial photographs and use of GIS techniques. The resulting loads are reduced by the amount reaching the groundwater, i.e., the leaching rate. Portions of the Club are also located within the Sengekontacket Pond watershed. The overall annual load from the Golf Club to Farm Pond is 116 kg.

Nitrogen Loading Input Factors: Landfill

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

This groundwater monitoring data included nitrate-nitrogen and ammonium-nitrogen data, but did not include total nitrogen measurements or a complete set of ammonium-nitrogen data. Based on a previous review of monitoring data from the groundwater plume associated with the Town of Brewster landfill (Cambareri and Eichner, 1993), MEP staff determined a relationship between ammonium-nitrogen and alkalinity concentrations (NH_4-N = 0.0352*ALK - 0.3565; r^2 = 0.82). This relationship was used to determine ammonium-nitrogen concentrations for Oak Bluffs landfill monitoring data where only nitrate-nitrogen and alkalinity data were available. Although nitrate-nitrogen and ammonium-nitrogen concentrations are not a complete measure of all nitrogen species, landfills do not generally release significant portions of dissolved organic nitrogen (Pohland and Harper, 1985).

MEP staff reviewed the available and estimated inorganic nitrogen monitoring data collected since 2006 in order to better match the timeframe associated with the estuary water quality monitoring data timeframe. This review found that the average of the inorganic nitrogen concentration in the three monitoring wells downgradient of the landfill is 3.69 ppm, while the average concentration in the upgradient well is 0.2 ppm. Using the difference of 3.49 ppm, the Martha's Vineyard-specific recharge rate, and the area of the landfill within the Farm Pond watershed, MEP staff estimated that the annual nitrogen load from the Oak Bluffs landfill is 68 kg yr^{-1}.

Nitrogen Loading Input Factors: Other

Other key factors in the nitrogen loading calculations are the recharge rate associated with impervious surfaces and natural areas. As discussed in Chapter III, Martha's Vineyard-specific recharge rates were developed and utilized based on comparison to the precipitation data in Oak Bluffs and results of the USGS groundwater modeling effort on Cape Cod. Other nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the Cape Cod Commission's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and Massachusetts DEP's Nitrogen Loading Computer Model Guidance (1999). Factors used in the MEP nitrogen loading analysis for the Farm Pond watershed are summarized in Table IV-1.

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

Nitrogen Concentrations:	mg/l
Road Run-off	1.5
Roof Run-off	0.75
Direct Precipitation on Embayments and Ponds	1.09
Natural Area Recharge	0.072
Wastewater	
Wastewater Coefficient	23.63
Oak Bluffs WWTF load – current in watershed (kg/yr)	132
Oak Bluffs WWTF load – buildout in watershed (kg/yr)	291
WWTF buildout effluent TN (mg/l)	4.2
Fertilizers[1]:	
Average Residential Lawn Size (sq ft):	1,820 in Farm Pond watershed; 400 in Ocean Park watershed
Residential Watershed Nitrogen Rate (lbs/1,000 sq ft)	0.55
Impervious Surfaces	
Buildings areas for single family residences (sq ft)	measured or 1,300 to 2,350 depending on area
Road area (sq ft)	measured or 31% of ROW area

Recharge Rates:	in/yr
Impervious Surfaces	42.2
Natural and Lawn Areas	28.7
Water Use/Wastewater:	
Existing developed residential parcels and buildout residential parcels:	Water use or town-wide average of 160 gpd
Commercial buildout additions[2]:	42 gpd /1,000 ft2 of building
Commercial building coverage of developed lots and buildout additions:	28%
Golf Course Fertilizers[3]	lbs N/1,000 sq ft
GREENS	3.8
TEES	**3.5**
Fairways	3.3
Roughs	2.5
Town of Oak Bluffs Landfill	
Area of capped solid waste within watershed (acres)	6.6
Estimated TN concentration in landfill plume (mg/l)	3.49
Estimated Total Nitrogen Load (kg/yr)	68.4

[1] Data from 1999 Martha's Vineyard lawn survey.
[2] No industrial buildout additions
[3] average nitrogen application rates based on information provided to MEP staff by course superintendents from 14 courses

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, parcels were assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel was located within a respective watershed. Following the assigning of boundary parcels, all large parcels were examined individually and were split (as appropriate) in order to obtain less than a 2% difference between the total land area of each sub-watershed and the sum of the area of the parcels within each sub-watershed.

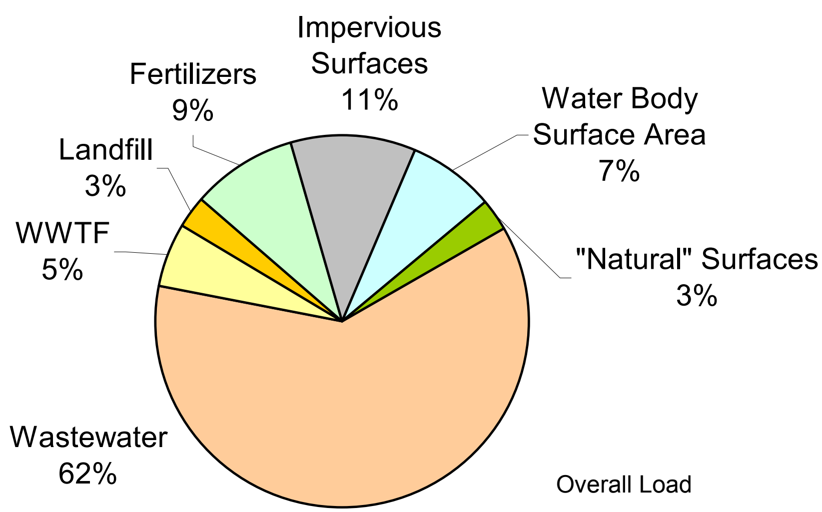
The review of individual parcels straddling watershed boundaries included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Building footprints for roof area calculations were either averaged for a given area or were measured directly off aerial photographs. Road areas are also based on direct measurement of road surfaces or 31% of the right-of-way area; this percentage is based on a MEP analysis of town-wide road and ROW areas within the Town of Harwich. Individualized information for parcels with atypical nitrogen loading (condominiums, golf courses, etc.) was also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the Farm Pond estuary. The assignment effort was undertaken to better define the sub-embayment loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

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

For management purposes, the aggregated estuary watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Farm Pond System, the major types of nitrogen loads are: wastewater (e.g., septic systems), the Oak Bluffs WWTF, the Oak Bluffs landfill, fertilizer, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge on natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-5). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model. No natural nitrogen attenuation occurs in the Farm Pond watershed because of the absence of freshwater ponds or streams.

Table IV-2. Farm Pond Nitrogen Loads. Presents nitrogen loads based on current conditions including nitrogen additions from the Oak Bluffs WWTF and landfill. Buildout loads include septic, fertilizer, and impervious surface additions from developable properties, as well as increased flows to the WWTF. All values are kg N yr^{-1}.

		Farm Pond N Loads by Input (kg/yr):								% of Pond Outflow	Present N Loads			Buildout N Loads		
Name	Watershed ID#	Wastewater	WWTF	Landfill	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Farm Pond System Total		**1482**	**132**	**68**	**217**	**264**	**179**	**68**	**432**		**2411**		**2411**	**2843**		**2843**
Farm Pond	1	1151	0	68	195	188	0	62	253		1663	0	1663	1917	0	1917
Ocean Park	2	332	132		23	76	0	6	179		569	0	569	747	0	747
Farm Pond Estuary Surface							179				179	0	179	179	0	179



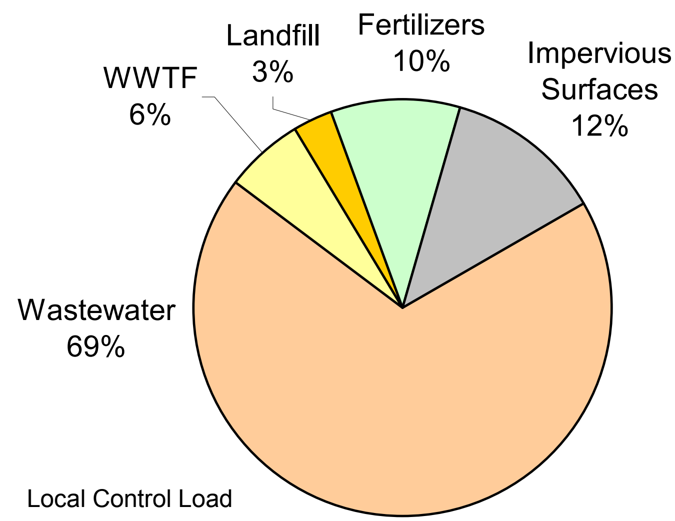


Figure IV-4. Land use-specific unattenuated nitrogen load (by percent) to the overall Farm Pond System watershed. “Overall Load” is the total nitrogen input within the watershed and direct atmospheric deposition to the estuary surface, while the “Local Control Load” represents only those nitrogen sources that could potentially be managed under local regulatory control.

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 Farm Pond modeling, MVC staff under the guidance of MEP staff reviewed individual properties for potential additional development. This review included assessment of minimum lot sizes based on current zoning, potential additional development on existing developed lots, a review of guesthouse provisions available under local regulations, and an estimate of future effluent discharge from the Oak Bluffs WWTF.

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 specified in current zoning to determine the total number of new lots. In addition, existing developed properties are reviewed for any additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence are assumed to have one additional residence at buildout. Most of the focus of new development is for properties classified as developable by the local assessor (state class land use codes 130 and 131 for residential properties). Properties classified by the Oak Bluffs assessor as “undevelopable” (e.g., codes 132 and 392) were not assigned any development at buildout. Commercially developable properties were not subdivided; the area of each parcel and the factors in Table IV-1 were used to determine a wastewater flow for these properties. Based on the buildout assessment completed for this review, there are 37 potential additional residential dwellings and 13,300 square feet of developable commercial land in the Farm Pond watershed. All additional residential parcels are in the Farm Pond sub-watershed; no additional parcels are indicated in the Ocean Park sub-watershed. All the parcels included in the buildout assessment of the overall Farm Pond watershed are shown in Figure IV-5.

Table IV-2 presents a sum of the additional nitrogen loads by sub-watershed for the buildout scenario. This includes the wastewater, fertilizer, and impervious surface loads from additional residential dwellings added, as well as wastewater and impervious surface loads from projected commercial buildout additions. The buildout load also includes the additions estimated for the Oak Bluffs WWTF when it reaches its design flow capacity. MVC staff completed an assessment of future flows based on the current peaking of flows in July and August. This evaluation found that the peak flow of 350,000 gallons per day and the accompanying decreases in the fall, winter, and spring resulted in an annual flow of 73 million gallons. This effluent flow was assigned the current flow-weighted average total nitrogen concentration of 4.2 ppm resulting in an annual buildout load from the Oak Bluffs WWTF of 1,162 kg with one quarter (291 kg/yr) assigned to Farm Pond in the MEP buildout scenario. Overall, buildout additions within the entire Farm Pond System watershed will increase the unattenuated loading rate by 18%.

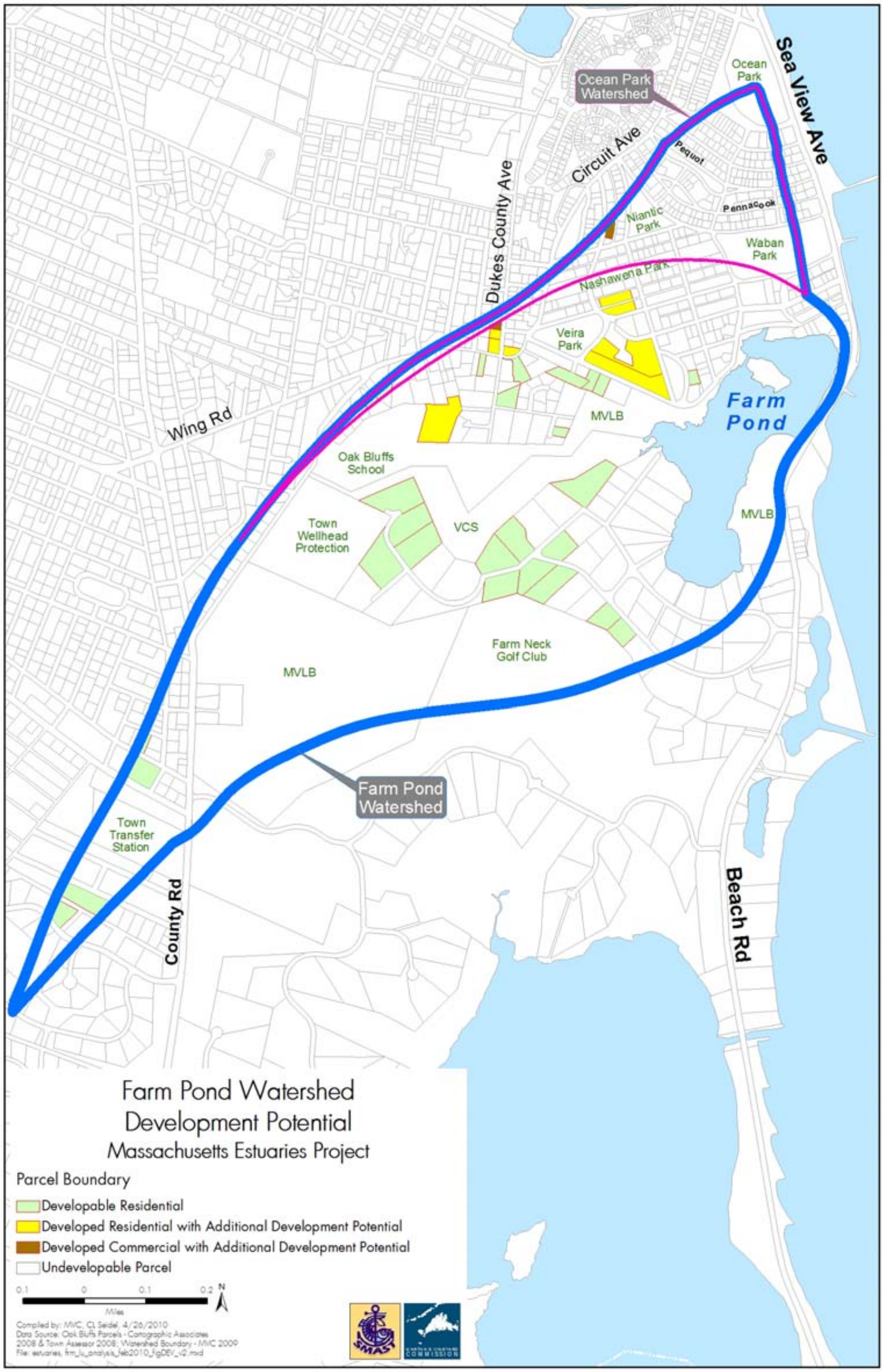


Figure IV-5. Developable Parcels in the Farm Pond watershed. Nitrogen loads in the buildout scenario are based on additional development assigned to these parcels plus greater effluent discharge from the Oak Bluffs WWTF.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out or sewering analysis) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the watershed of the Farm Pond System were based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1). If all of the nitrogen applied or discharged within a watershed reaches an embayment, the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport is through groundwater in sandy outwash aquifers. The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. This is the case for the Farm Pond watershed. Unlike most watersheds in southeastern Massachusetts, nitrogen does not pass through a surface water ecosystem on its path to the adjacent embayment. It is in these surface water systems that the needed conditions for nitrogen retention and denitrification exist. As there were no streams or great fresh ponds within the Farm Pond watershed, the watershed loading approach considered that nitrogen reaching the water table was transported without attenuation in the groundwater system until discharge to the estuary.

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

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

IV.3.1 Sediment-Water column Exchange of Nitrogen

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

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

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

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

IV.3.2 Method for Determining Sediment-Water column Nitrogen Exchange

For the Farm Pond Embayment System, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples (8 cores) were collected from 7 sites (Figure IV-6) in July-August 2006, focusing on obtaining an areal distribution that would be representative of nutrient fluxes throughout the pond but also considering tributary basins such as that on the southern end of Farm Pond. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The number of core samples from each site (Figure IV-6) per incubation are as follows:

Farm Pond System Benthic Nutrient Regeneration Cores

- FRM-1 1 core (South Basin)
- FRM-2 1 core (Middle Basin)
- FRM-3 1 core (Middle Basin)
- FRM-4 1 core (Middle Basin)
- FMR-5 1 core (North Basin)
- FRM-6/7 2 cores (North Basin)
- FRM-8 1 core (North Basin)

Sampling was distributed throughout the pond such that the results for each site could be combined to calculate 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 (Town of Oak Bluffs Department of Public Works), the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and orthophosphate (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 [*508-910-6325*]. The laboratory follows standard methods for saltwater analysis and sediment geochemistry.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

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

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

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

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

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-7).

Figure IV-6. Farm Pond System locations (blue diamonds) of sediment sample collection for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-3.

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

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

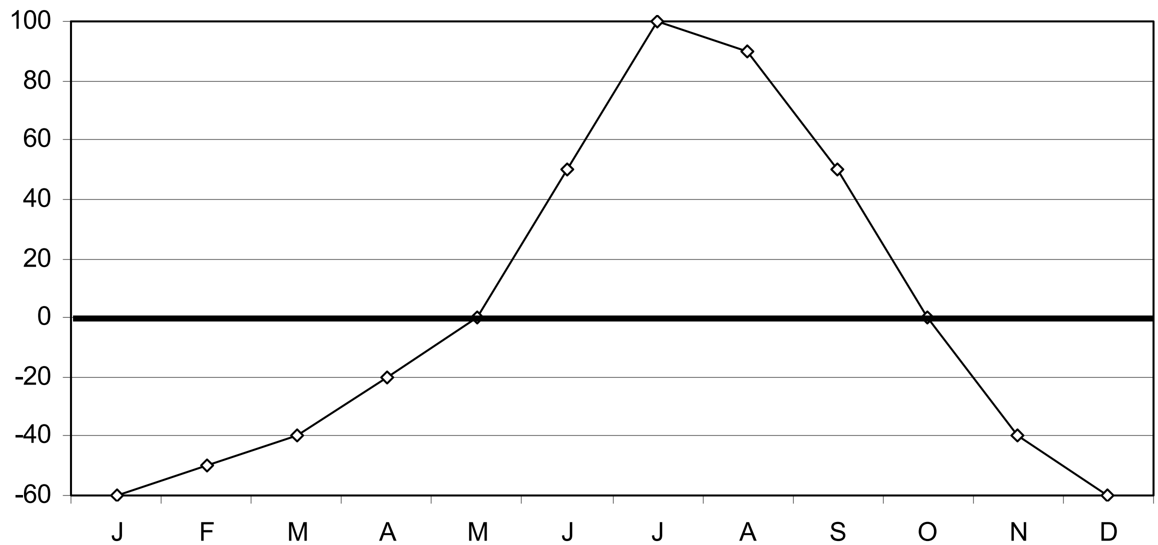


Figure IV-7. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Sediment Nitrogen Release by Standard Core Approach: Sediment sampling was conducted throughout the embayment basin of this system. Samples were collected in the basin north of Woody Island and throughout the larger basin to the south. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content, as well as sediment type and an analysis of each site's tidal flow velocities. As expected flow velocities are generally low throughout Farm Pond except in the immediate vicinity of the inlet culvert. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (Chapter V). Based upon the low velocities, a water column particle residence time of ~8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins). Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas that are net nitrogen sinks for the aquatic system. This approach has been previously validated in outer Cape Cod embayments (Town of Chatham) 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 other enclosed basins (with little freshwater inflow), where the fluxes can be determined by multiple methods. In this case the rate of sediment regeneration determined from incubations was comparable to that determined from whole system balance.

Rates of net nitrogen release or uptake from the sediments within the Farm Pond Embayment System were comparable to other embayments of similar depth and configuration in southeastern Massachusetts. There was a clear pattern of sediment N flux. While sediments throughout both basins were showing net nitrogen uptake, the smaller northern basin had significantly higher rates than the southern basin, -25.7 and -5.9 mg N m^{-2} d^{-1}, respectively. The difference in sediment nitrogen flux reflects the configuration of the 2 basins and may also be correlated with the occurrence of eelgrass beds throughout the southern basin, with only sparse coverage in the northern basin. The sediments reflect the depositional nature of these basins, both basins having surface sediments comprised of soft organic muds with only a thin oxidized surface layer.

The pattern of sediment nitrogen flux is similar to other enclosed basins within southeastern Massachusetts with similar sediment characteristics. The measured nitrogen flux rates in Farm Pond are similar to those in the single central basin of Rushy Marsh, Barnstable, MA (-19.1 mg N m^{-2} d^{-1}), which is also a small tidally restricted embayment. Similarly, the depositional basins within the Parkers River Estuary, Seine Pond and Lewis Pond were found to have net nitrogen uptake by their sediments of -16.9 and -11.8 mg L^{-1}, respectively, and the shallow enclosed tributary coves within Edgartown Great Pond also had comparable rates (-8.9 to -16.0, Wintucket, Turkeyland, Slough, Jobs Neck Coves). The sediment nitrogen flux in Farm Pond appears 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 restricted tidal exchange. Net nitrogen flux rates for use in the water quality modeling effort for the component sub-basins of the Farm Pond Embayment System (Chapter VI) are presented in Table IV-3.

Water-column average total nitrogen and salinity levels were available from the Water Quality Monitoring Program for 2003-2009. Note that there is little to no horizontal gradient in nitrogen or salinity across the pond (Chapter VI).

Table IV-3. Rates of net nitrogen return from sediments to the overlying waters of the Farm Pond Embayment System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July - August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			i.d. *
	Mean	S.E.	N	
Farm Pond Embayment System				
North Basin	-25.7	4.4	4	FRM-5, 6,7, 8
South Basin	-5.9	5.1	4	FRM-1, 2, 3, 4

* Station numbers refer to Figures IV-6.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This hydrodynamic study, funded by the Massachusetts Department of Ecological Restoration, was performed for Farm Pond, located within the town of Oak Bluffs, Massachusetts, on the northeastern side of Martha's Vineyard. A topographic map detail in Figure V-1 shows the general study area situated on Nantucket Sound. Farm Pond is a shallow coastal pond that is open to Nantucket Sound through a 4 ft diameter culvert. The mean depth of the Pond is only 1.2 feet Mean Low Water (MLW). The total surface coverage of the Farm Pond system is approximately 42 acres, which includes eight acres of salt marsh. Some of the low-lying upland areas proximate to the Pond have been developed, and the structures in these areas are exposed to a risk of flooding during storm events. A photo of the lowest structure on the Pond is presented in Figure V-2. The ground elevation under this pile supported structure is approximately 4.5 feet MLW.

Circulation in Farm Pond is dominated by tidal exchange with Nantucket Sound. From measurements made in the course of this study, the average offshore tide range offshore the Pond is 2.0 feet. By flow restrictions caused by the culvert, the average tide range in the Pond is only 0.5 ft. Though this range is small, it is twice the tide range that was estimated in the original culvert design analysis (IEP, 1991). Because of the increased tide range, the present tide prism is also twice as large as was originally estimated.

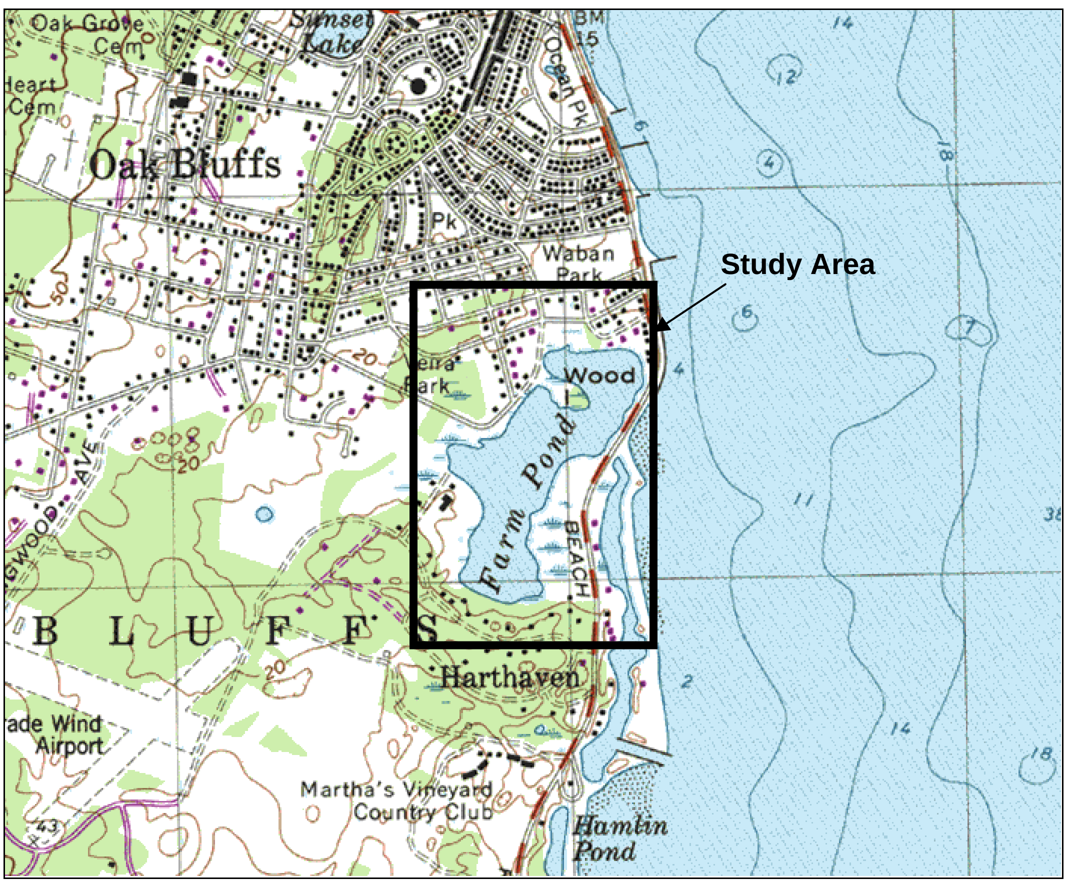


Figure V-1. Topographic map of Oak Bluffs, with an outline designating the study area of the Farm Pond system.

Figure V-2. Low-lying property along the Farm Pond shoreline. Ground elevation under this structure is approximately 4.5 feet MLW. (Photo source: Bill Wilcox, Martha's Vineyard Commission)

The existing inlet configuration has been in place since the 1990's. Before the present inlet culvert was placed under Beach Road, the Pond exchanged tidal flows with Nantucket sound through Harthaven Inlet. The position of the relic inlet relative to the present inlet is shown in Figure V-3. Repeated blockage of the narrow channel between Farm Pond and Harthaven Inlet lead to the reconfiguration of the Farm Pond inlet as it exists now (IEP, 1988). The old channel between Farm Pond and Harthaven Inlet no longer exists as it is no longer in any sort of serviceable condition.

The hydrodynamic study of Farm Pond proceeded as three component efforts. In the first portion of the study, bathymetry and tide data were collected in order to accurately characterize the physical system, and to provide data necessary for the modeling portion of the study. The bathymetry survey of Farm Pond was performed to determine the variation of embayment depths throughout the system. This survey addressed the previous lack of adequate bathymetry data for this area. In addition to the bathymetry survey, tides were recorded in the Pond and in Nantucket Sound for 34 days. This tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of the Farm Pond was developed in the second portion of this study. Using the bathymetry survey data, a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data from Nantucket Sound were used to define the open boundary condition that drives the circulation of the model, and 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.

Finally, the calibrated hydrodynamic model of Farm pond was used to perform an evaluation of a range of possible inlet modifications, in order to assess relative flushing performance of each modeled scenario over present conditions. A particle tracking model was employed to further quantify the differences of each modeled scenario.

Figure V-3. Oblique aerial photo of Farm Pond (below Beach Road) and Nantucket Sound (above Beach Road) looking east. The location of the present culvert and the abandoned Farm Pond and Harthaven inlets are indicated. (Photo source: New England District, US Army Corps of Engineers)

V.2 DATA COLLECTION AND ANALYSIS

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

V.2.1 Bathymetry Data

A bathymetric survey of Farm Pond was performed October 21, 2005. An Odon fathometer was used to take continuous soundings of the bottom as the motor skiff survey vessel moved through the water. Positioning data were collected using a differential GPS. The actual survey paths followed by the survey craft are shown in Figure V-4. The resulting bathymetric surface created by interpolating the data to a finite element mesh is shown in Figure V-5. All bathymetry were tide corrected using tide data collected in the Pond. The data were also surveyed to the local Mean Low Water (MLW) datum (determined by the National Geodetic Survey), using an US Army Corps of Engineers (USACE) monument.

Figure V-4. Transects from the October 2005 bathymetry survey of Farm Pond. Yellow markers show the locations of the three tide recorders deployed for this study.

Results from the survey show that the deepest point in Farm Pond is located in the southern portion of the pond basin, and is -5.9 ft MLW. The Pond is generally much shallower, with an average depth of approximately -1.2 feet MLW.

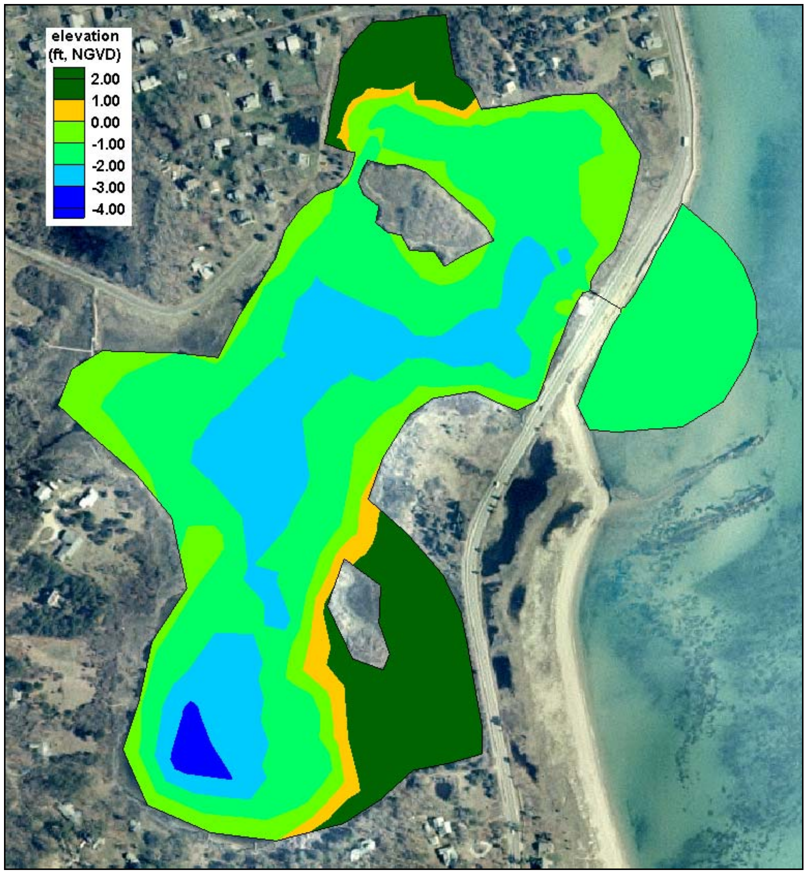


Figure V-5. Bathymetry data interpolated to the finite element mesh used with the RMA-2 hydrodynamic model. Contours represent the bottom elevation relative to mean low water (MLW). Data source used to develop the grid mesh is the October 2005 survey of the Pond.

V.2.2 Tide Data Collection and Analysis

Tide data records were collected concurrently at two gauging stations, the first located inside Farm Pond and the second located offshore in Nantucket Sound (offshore Sengekontacket Pond). The position of the Farm Pond gauge is shown in Figure V-4. The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 34-day period between October 18 and November 22, 2005. The elevation of each gauge was surveyed relative to the local MLW datum. The Nantucket Sound tide record was used as the open boundary condition of the hydrodynamic model. Data from inside the Pond 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.

Plots of the tide data from the three gauges are shown in Figure V-6 for the entire 34-day deployment. The spring-to-neap variation in tide range is discernable in these plots, though not easily, due to the unique characteristics of the tide in this area of Nantucket Sound.

From the plot of the data from Nantucket Sound, the tide reaches its minimum neap tide range of approximately one foot around October 28. About seven days before and after this date, the spring tide range is approximately 3 feet. A visual comparison between tide elevations offshore and in the Pond shows that the tide amplitude in Farm Pond is considerably smaller than offshore. This loss of amplitude is described as tidal attenuation. In Farm Pond, the attenuation of the tide signal from Nantucket Sound is due to flow restrictions caused by the culvert that is the sole connection between the Pond and the Sound.

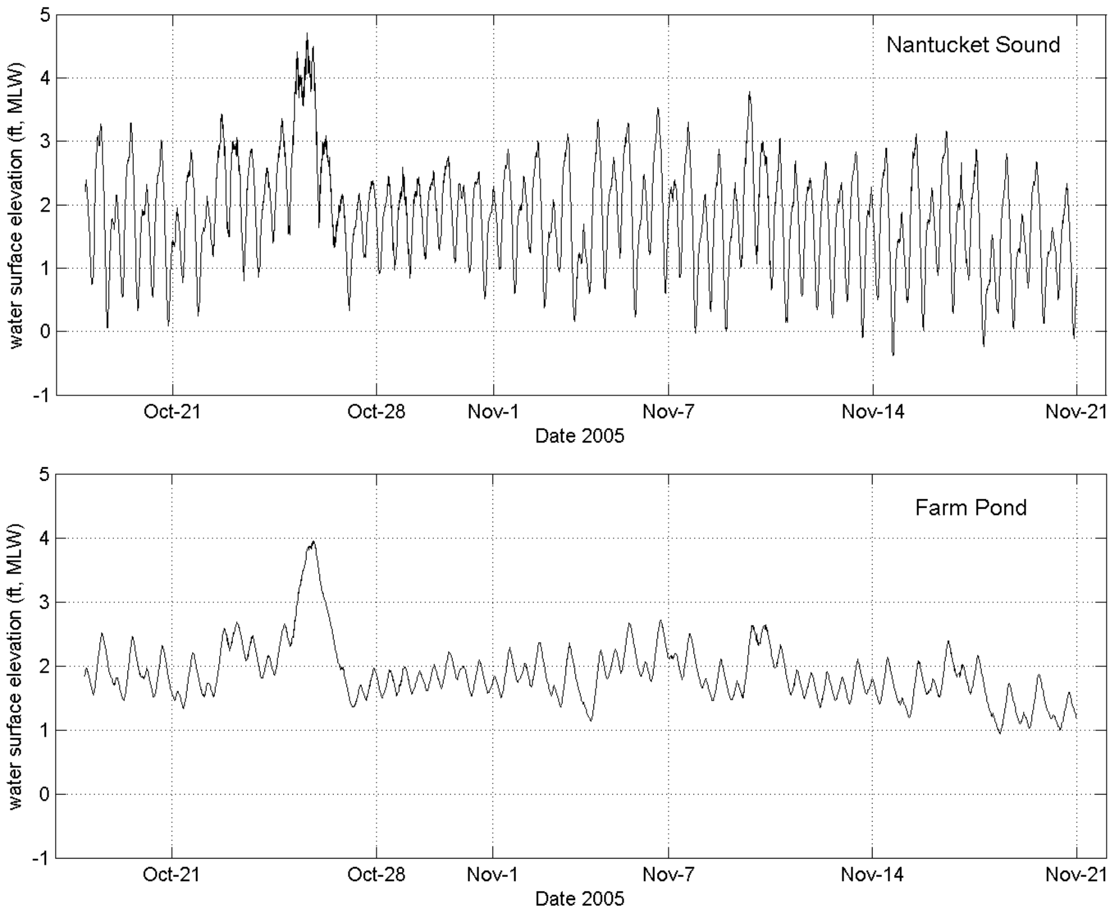


Figure V-6. Plots of observed tides for Farm Pond, for the 34-day period between October 18 and November 21, 2005. The top plot shows tides offshore the Pond in Nantucket Sound and the bottom plot shows tides in Farm Pond. All water levels are referenced to the NOS Island Mean Low Water (MLW) datum.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 34-day records. These datums are presented in Table V-1. 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. The small mean tide range of 2.0 feet calculated for the offshore record is typical for the areas of Vineyard and Nantucket Sounds between Falmouth and Martha's Vineyard.

Frictional damping is evident in the reduction of the mean tide range in Farm Pond, compared to the mean range offshore. The tide range in the Pond is only 0.5 feet, or 25% of the mean offshore range. Damping not only affects the range of the observed tide, it also causes a time lag in the time of high and low tide. Figure V-7 shows how the time of high and low tides lags approximately two hours from the offshore tide.

A more thorough 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.

A harmonic analysis was performed on the time series from each gauge location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The 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 Farm Pond and offshore data records. 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 0.82 feet. The total range of the M_2 tide is twice the amplitude, or 1.64 feet. The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.3 feet and 0.2 respectively. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, are a smaller portion of the to the total tide signal, with amplitudes of 0.06 feet and 0.19 feet, respectively. The M_4 and M_6 tides are higher frequency harmonics of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water. The constituent with largest amplitude inside the Pond is the M_2, which has a range of only 0.18 feet, or only 22% of the amplitude of the offshore the M_2.

Table V-1. Tide datums computed from 34-day records collected offshore and in Farm Pond in October and November 2005. Datum elevations are given relative to the local NOS MLW datum.

Tide Datum	Nantucket Sound (feet)	Farm Pond (feet)
Maximum Tide	4.7	3.9
MHHW	3.0	2.3
MHW	2.7	2.1
MTL	1.7	1.9
MLW	0.7	1.6
MLLW	0.4	1.5
Minimum Tide	-0.4	0.9

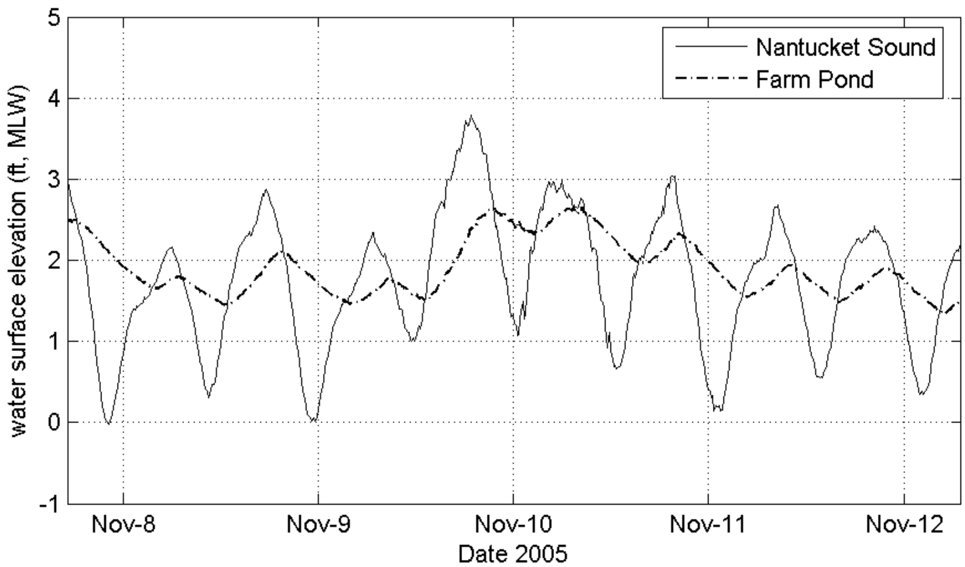


Figure V-7. Four-day tide plot showing tides measured in Farm Pond (dot-dashed line) and Nantucket Sound (solid line). Demonstrated in this plot is the frictional damping effect caused by the culvert connection between Farm Pond and the Sound. The damping effects are seen as a reduction in tidal amplitude, as well as the lag in time of high and low tides from the offshore tide.

Table V-2. Tidal Constituents computed for Farm Pond and Nantucket Sound (off Sengekontacket) tide records, October to November 2005.

	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
Nantucket Sound	0.82	0.21	0.07	0.06	0.19	0.30	0.24
Farm Pond	0.18	0.01	0.01	0.02	0.03	0.15	0.12

The observed astronomical tide is therefore the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-8.

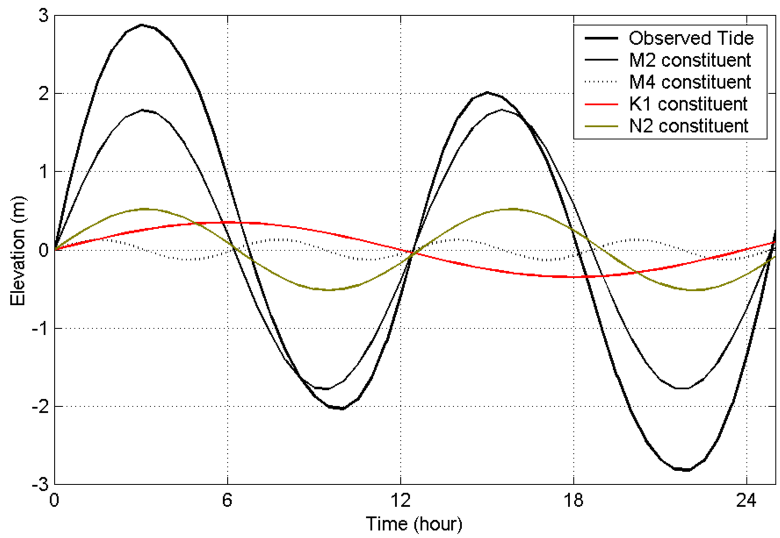


Figure V-8. Example of an observed astronomical tide as the sum of its primary constituents.

In addition to the tidal analysis, the data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. These other processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow. The results of an analysis to determine the energy distribution (or variance) of the measured water elevation records for Farm Pond and Nantucket Sound 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 resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary.

Figure V-9 shows the comparison of the measured tide from Nantucket Sound, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual. Easily seen in the plot of Figure V-9, periodic storm events have a significant effect on water level changes in the sound. A storm which passed though the region on October 25 increased water levels in the sound nearly 3 feet over the astronomical portion of the tide. From the tide data plot in Figure V-6, it is apparent that this storm surge caused a similarly large increase in water levels in Farm Pond.

Table V-3 shows that the variance of tidal energy was largest in the offshore signal; as should be expected given the large degree of tidal attenuation between Nantucket Sound and the Pond basin. The analysis also shows that tides are responsible for approximately 68% of the water level changes in Nantucket sound, but only 19% inside the Pond. This indicates that water levels in the pond are influenced mostly by atmospheric effects (i.e., winds and barometric pressure), which is perfectly reasonable considering the micro-scale tide range of the Pond.

Table V-3. Percentages of Tidal versus Non-Tidal Energy for Farm Pond and Nantucket Sound tide records, October to November 2005.

TDR LOCATION	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Nantucket Sound	0.703	68.0	32.0
Farm Pond	0.209	19.0	81.0

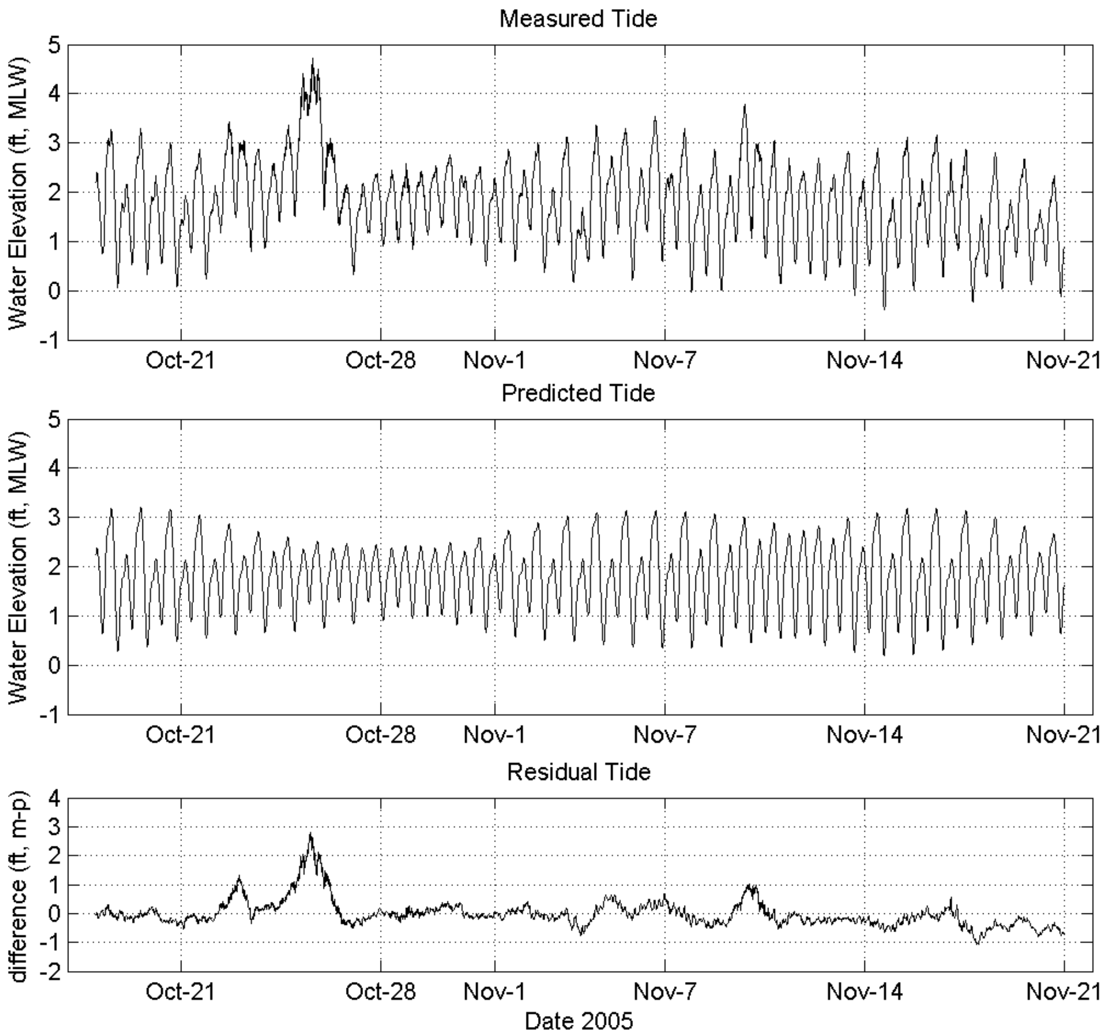


Figure V-9. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 21 individual tide constituents determine in the harmonic analysis of the Nantucket Sound gauge data, collected offshore Sengekontacket Pond. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (r=m-p).

V.3 HYDRODYNAMIC MODELING

For the modeling of the Farm Pond system, Applied Coastal utilized a state-of-the-art computer 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 (Wood, *et al*, 1999).

V.3.1 Model Theory

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

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 2001 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of the Farm Pond grid based on the tide gauge data collected offshore in Nantucket Sound. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several model calibration simulations for the system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. A 2001 digital aerial orthophoto and the recent bathymetry survey data were imported to SMS, and a finite element grid was generated to represent the estuary. The aerial photograph was used to determine the land boundary of the system, as well as determine the surface coverage of salt marsh. The bathymetry data were interpolated to the developed finite element mesh of the system. The completed grid consists of 1,386 nodes, which describe 524 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth is -5.9 ft (MLW datum) in the southern portion of the Pond, and the maximum modeled marsh plain elevation is 2.1 ft. In the model grid, a typical marsh plain elevation of +2.1 ft (MLW datum) was used, based on the computed MHW elevation computed for the tide gauge data record from the Pond. The completed grid mesh of the Farm Pond system is shown in Figure V-10.

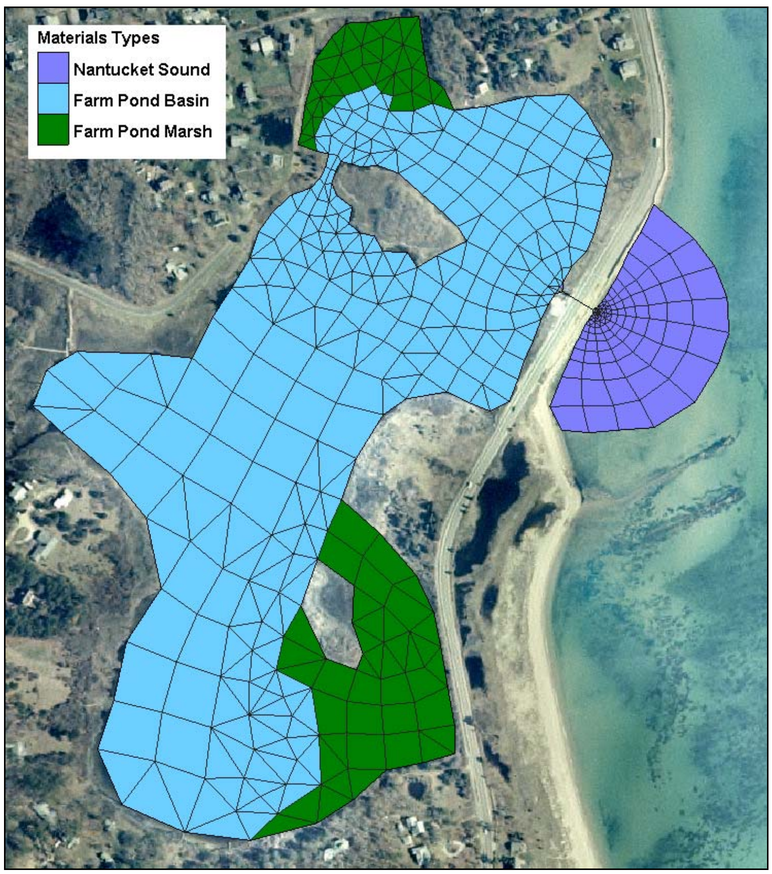


Figure V-10. Plot of hydrodynamic model grid mesh for Farm Pond. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Farm Pond. 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.

V.3.2.2 Boundary condition specification

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

V.3.2.3 Calibration

After developing the finite element grids, and specifying boundary conditions, the model for the Farm Pond 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 inside the Pond (i.e., from the TDR deployments). Initially, the model was calibrated to obtain visual agreement between modeled and measured tides.

Once visual agreement was achieved, an approximate five-day period (10 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section 2. The five-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibration was performed for a five-day period beginning November 10, 2005 at 1845 EDT. This representative time period included the spring tide range of conditions, where the tide range and tidal currents are greatest.

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 for the five-day period beginning October 27, 2005 at 2300 EDT.

The calibrated model was used to analyze existing detailed flow patterns and compute residence times. The flushing analysis is based on the 8.25 day period (16 tide cycles) beginning November 9, 2005, at 1845 EDT. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire seven-day simulation. 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 0.025 and 0.070 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 Farm Pond, versus the marsh plain areas of the 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-4.

Table V-4. Manning’s Roughness coefficients used in simulations of Farm Pond. These embayment delineations correspond to the material type areas shown in Figure V-10.

System Embayment	Bottom Friction
Farm Pond Inlet	0.025
Farm Pond Culvert	0.030
Main Basin Farm Pond	0.030
Farm Pond Marsh	0.070

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 between 50 and 100 lb-sec/ft^2. Higher values (up to 200 lb-sec/ft^2) were used on the marsh plain, to ensure solution stability.

V.3.2.3.c Marsh porosity processes

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

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

A best-fit of model predictions for the first TDR deployment was achieved using the aforementioned values for friction and turbulent exchange. Figures V-11 and V-12 illustrate the five-day simulation periods along with 50-hour sub-section, for the separate calibration and verification model runs. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled systems. Two dominant tidal constituents were selected for constituent comparison: the K_1 and M_2. Measured tidal constituent amplitudes are shown in Table V-5 for the calibration and verification simulations. The constituent amplitudes shown in this table differ from those in Table V-2 because constituents were computed for only the separate five-day sub-sections of the 34-days represented in Table V-2. In Table V-6, error statistics are shown for each model run.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The errors associated with tidal constituent amplitude for both the calibration and verification simulations were on the order of 0.01 ft, which is of the same order magnitude of the accuracy of the tide gages (0.032 ft). Time lag errors (Table V-6) 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.

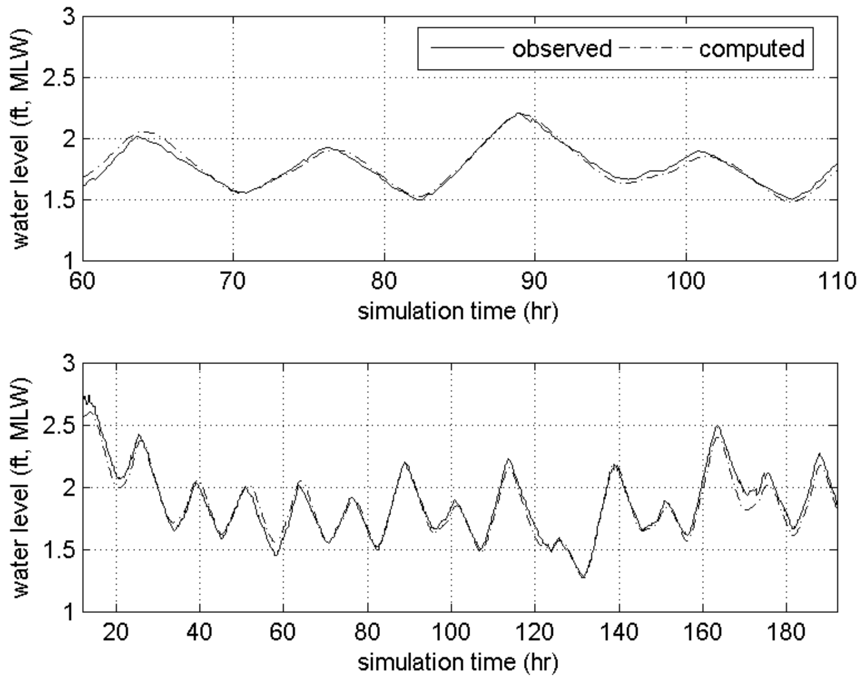


Figure V-11. Comparison of model output and measured tides for the TDR location in Farm Pond for the final calibration model run (starting November 10, 2005 at 1845 EDT). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

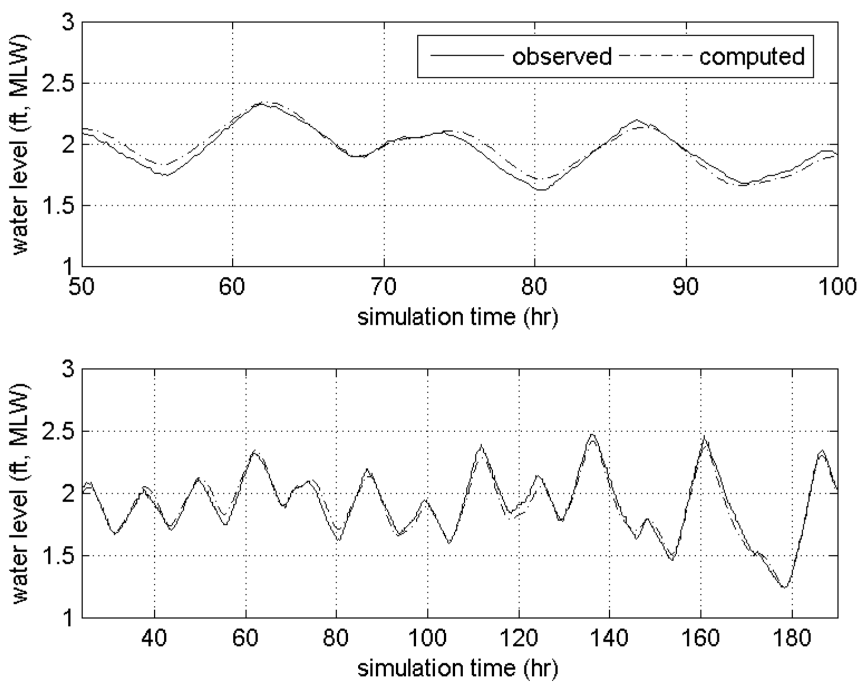


Figure V-12. Comparison of model output and measured tides for the TDR location in Farm Pond for the verification model run (starting October 27, 2005 at 2300 EDT). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

Table V-5. Model verses measured tidal constituent amplitude comparison, for the two major tide constituents in Farm Pond, from the calibration and verification model simulation periods		
Calibration		
Tide Constituent	M_2	K_1
Measured amplitude (ft)	0.21	0.13
Modeled amplitude (ft)	0.22	0.11
Error (ft)	-0.01	0.02
Verification		
Tide Constituent	M_2	K_1
Measured amplitude (ft)	0.19	0.13
Modeled amplitude (ft)	0.18	0.11
Error (ft)	0.01	0.02

Table V-6. Error statistics for the Farm Pond hydrodynamic model, for model calibration and verification.	
Calibration	
R^2 correlation	0.97
RMS error (ft)	0.04
M_2 phase error (min)	-4.0
Verification	
R^2 correlation	0.94
RMS error (ft)	0.05
M_2 phase error (min)	-4.8

V.3.4 Model Circulation and Flushing Characteristics

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

As an example, from the calibration model run of the Farm Pond system, ebb velocities in the culvert between the Pond and the Sound are slightly larger than velocities during maximum flood. The maximum depth-averaged ebb velocities in the model are approximately 6.6 feet/sec, while maximum flood velocities are about 4.8 feet/sec.

In addition to depth averaged velocities, the total flow rate of water flowing through the inlet culvert can be computed with the hydrodynamic model. For the flushing analysis in the next section, flow rates where computed through the culvert. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-13. The results show that though maximum velocities occur during ebbing tides, the maximum flow rates occur during flood tides in this system. This is possible because the cross-sectional area of flow in the culvert changes as the tide elevation changes, so at times a smaller velocity with a larger flow area will result in more flow than a larger velocity and a smaller cross-sectional area. During spring tides, the maximum flood flow rates reach 80 ft^3/sec in the inlet culvert. Maximum ebb flow rates during spring tides are slightly less, or about 60 ft^3/sec.

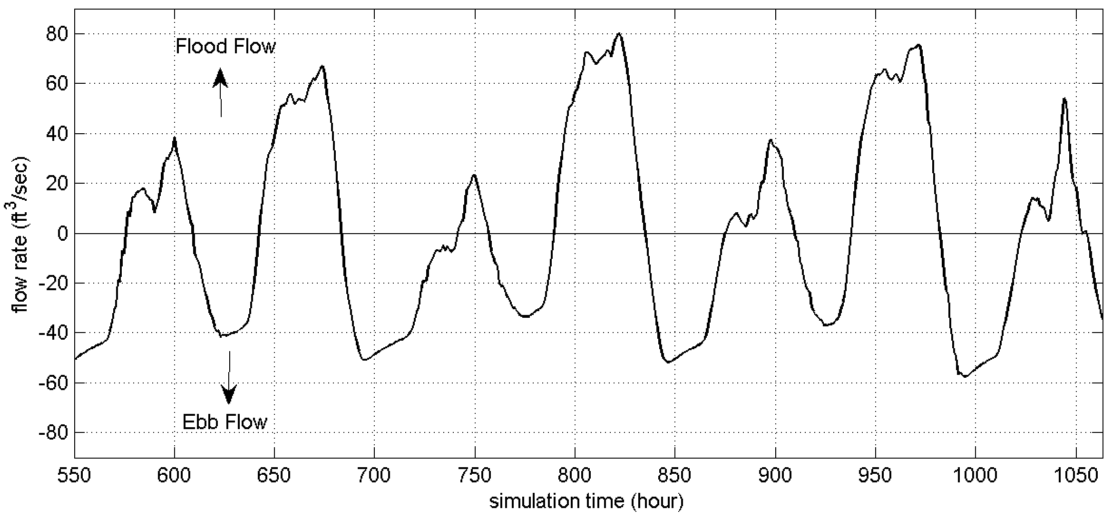


Figure V-13. Time variation of computed flow rates at the Farm Pond culvert. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flow indicated flooding tide flows, while negative flow indicates ebbing tide flows.

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through each inlet, even with only a 0.5 foot tide range, the primary mechanism controlling estuarine water quality within the modeled Farm Pond system is tidal exchange with Nantucket Sound. A rising offshore tide creates a slope in water surface from the ocean into the modeled systems. Consequently, water flows into (floods) the system. Similarly, Pond drains into the open waters of Nantucket Sound on an ebbing tide. This exchange of water between each system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of each system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

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

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

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

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 from offshore provide the only means of reducing the high nutrient levels. For the Farm Pond system this approach is applicable, since it assumes the main system has relatively low quality water relative to Nantucket Sound.

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the estuary faster than the tidal circulation can flush the system. Neither are low residence times an indicator of high water quality if the water flushed into the estuary is of poor quality. Advanced understanding of water quality will be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Farm Pond system.

RMA-2 model results were used to compute the Pond residence time. The residence time of the Pond was 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 the system over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Sub-embayment mean volumes and average tide prisms computer for Farm Pond system are presented in Table V-7, along with the resulting residence time.

Table V-7. Farm Pond mean volume and average tidal prism with computed flushing time.

Mean Volume (ft^3)	5,167,000
Tide Prism Volume (ft^3)	738,000
System Residence Time (days)	3.62

Residence times were averaged for the tidal cycles comprising a representative 7.25 day period (14 tide cycles). The modeled time period used to compute the flushing rates overlapped the modeled calibration period, and included the transition from neap to spring tide conditions. Since the 7.25-day period used to compute the flushing rate represents average tidal conditions, it provides the most appropriate method for determining the mean flushing rate of the system.

The computed flushing rate for Farm Pond shows that the system does not flush efficiently, and that the average tidal prism is small compared to the mean system volume. This is also evident by the fact that the system volume is seven times greater than the tidal prism. A flushing time of 3.62 days for the entire estuary shows that on average, water is resident in the system more than three days.

The results of this present analysis show that the tide prism and tide range are significantly greater than what was intended. The original analysis performed to support the design of the culvert (IEP, 1991) determined that with a 47 inch by 72 inch culvert the tide range in the Pond would be 0.26 feet, resulting in an average 378,000 ft^3 tide prism. The actual installed culvert has a smaller circular cross section, but has an average tide range of 0.50 feet, resulting in a tide prism that is twice the volume of the original 1991 estimate.

Generally, possible errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. In this study, the most significant errors associated with the bathymetry data result from the process of interpolating the data to the finite element mesh, which was the basis for all the flushing volumes used in the analysis. Also some error may result from the estimate of marsh plain elevation based on the MHW elevation determined for the Pond. Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. However, water exiting a small sub-embayment on a relatively calm day may not completely mix with estuarine waters. In this case, the “strong littoral drift” assumption would lead to an under-prediction of residence time. Since littoral drift in the upper portion of Nantucket Sound typically is strong because of the effects of strong tidal currents in the Sound and local winds induce tidal mixing within the regional estuarine systems, the “strong littoral drift” assumption only will cause minor errors in residence time calculations. Based on our knowledge of estuarine processes, we estimate that the combined errors due to bathymetric inaccuracies represented in the model grid and the “strong littoral drift” assumption are within 10% to 15% of “true” residence times.

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

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

VI.1.1 Hydrodynamics and Tidal Flushing in the 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 Farm Pond 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 a five-day period beginning November 10, 2005 at 1845 EDT. This period corresponds to that used in the flushing analysis presented in Chapter V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic “steady state”, and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

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

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. The multi-year averages present the “best” comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. Six years of data (collected between 2003 and 2009) were available at FAM-1 and FAM-3. Five years of data were available at FAM-2.

Table VI-1. Measured data and modeled Nitrogen concentrations for the Farm Pond estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data represented in this table were collected in the summers of 2002 through 2008.

Sub-Embayment	MEP monitoring station	data mean	s.d. all data	N	model min	model max	model average
North Basin	FAM-1	0.516	0.114	18	0.466	0.520	0.496
Mid Pond	FAM-2	0.505	0.135	16	0.440	0.507	0.480
South Basin	FAM-3	0.530	0.178	17	0.506	0.510	0.508
Nantucket Sound	NTKS	0.294	0.062	4	-	-	-

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 Farm Pond estuarine system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of Farm Pond. 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 Cape Cod Commission watershed loading analysis, 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 Farm Pond system.

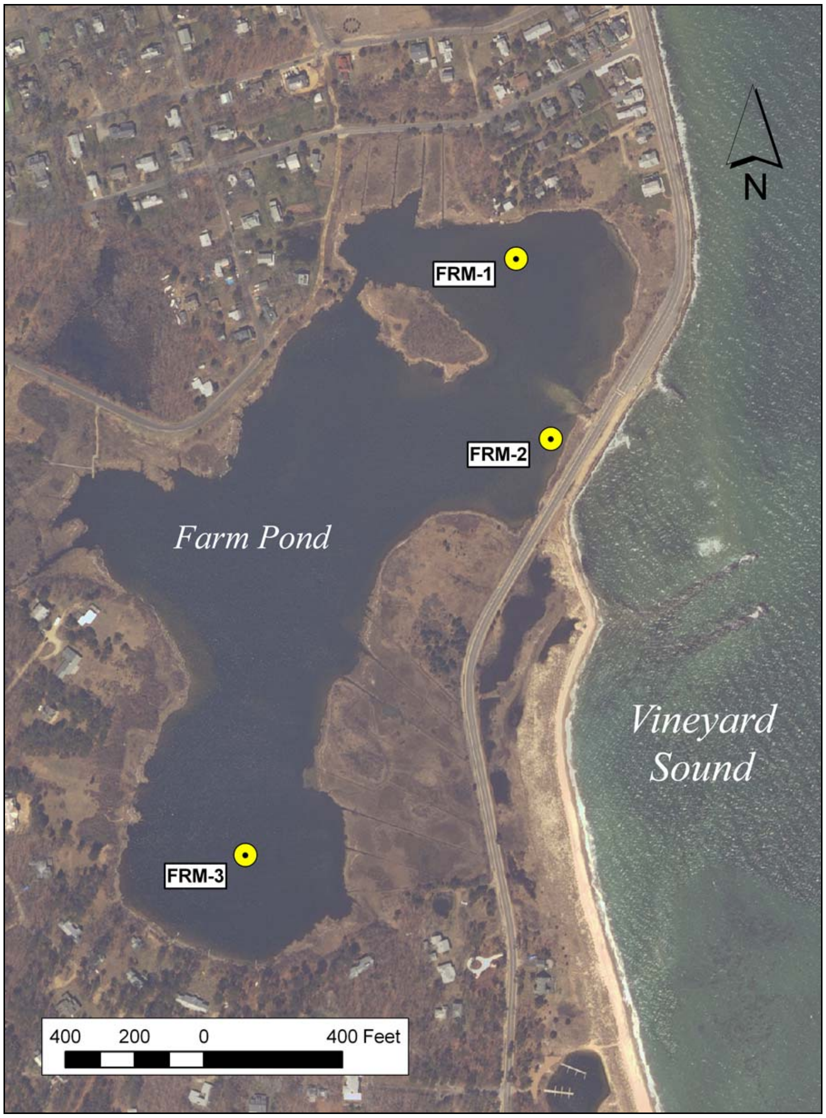


Figure VI-1. Estuarine water quality monitoring station locations in the Farm Pond estuary system. Station labels correspond to those provided in Table VI-1.

VI.2.1 Model Formulation

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

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

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

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

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

VI.2.2 Water Quality Model Setup

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

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

VI.2.3 Boundary Condition Specification

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

The loadings used to model present conditions in the Farm Pond system are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For most areas of Farm Pond, especially the deeper south basin, the net benthic flux is negative which indicates a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in Nantucket Sound was set at 0.294 mg/L, based on SMAST data.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Farm Pond System Total	**5.970**	0.490	-0.892

VI.2.4 Model Calibration

Calibration of the total nitrogen model of Farm Pond 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 coastal 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 mid-point between maximum modeled TN and average modeled TN was compared to mean measured TN data values, at each water-quality monitoring station. The calibration target would fall 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 Farm Pond estuary system.
Embayment Division	E m^2/sec
Offshore	0.10
Farm Pond	1.00
Marsh	0.05
Culvert	0.05

Also presented as Figure VI-3 is a unity plot comparisons of measured data verses modeled target values for each station in the system. Computed root mean squared (rms) error is less than 0.02 mg/L, which demonstrates a good fit between modeled and measured data for this system.

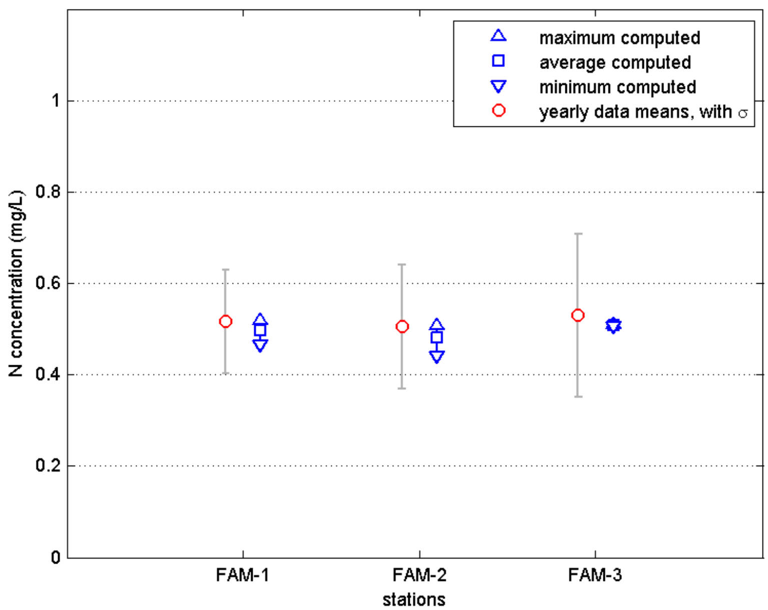


Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Farm Pond system. Station labels correspond with the MEP IDs provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation 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

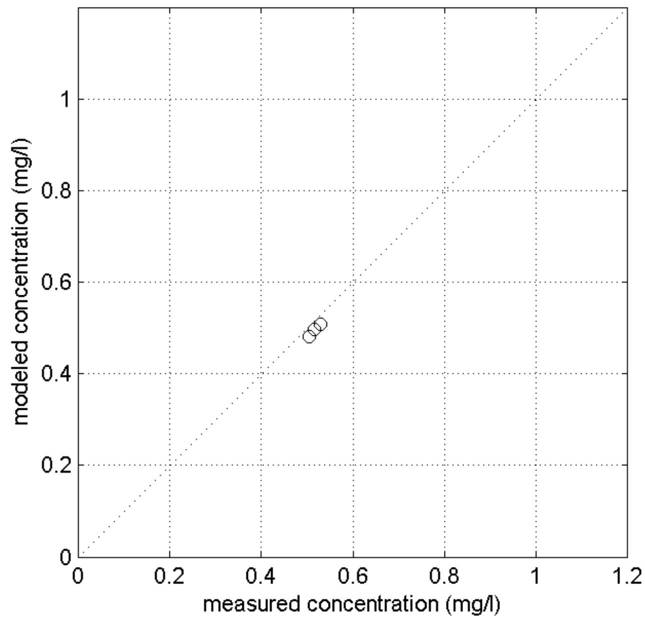


Figure VI-3. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed RMS error for the model is 0.02 mg/L.

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

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Farm Pond system using salinity data collected at the same stations as the nitrogen data. 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 0.8 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, and groundwater inputs. The open boundary salinity was set at 30.0ppt. Groundwater was input to the model using a 0 ppt salinity concentration. The total groundwater input to the model was 1.44 ft^3/sec (3,520 m^3/day). Groundwater flows were distributed evenly in the model through the use of several designated input elements positioned along the model's land boundary.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the Farm Pond, 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.

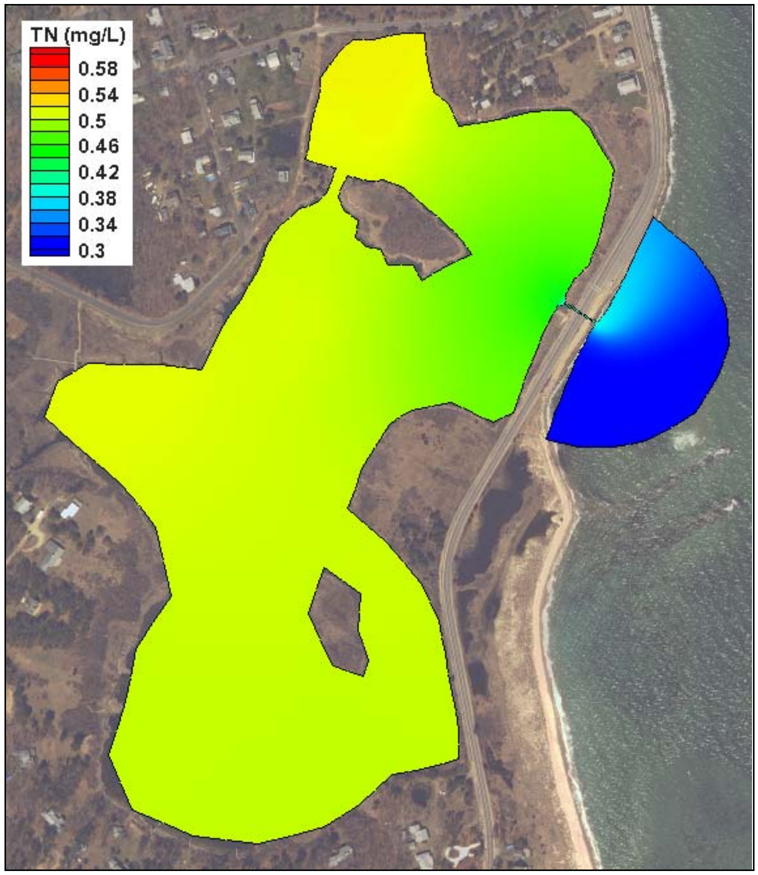


Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Farm Pond system.

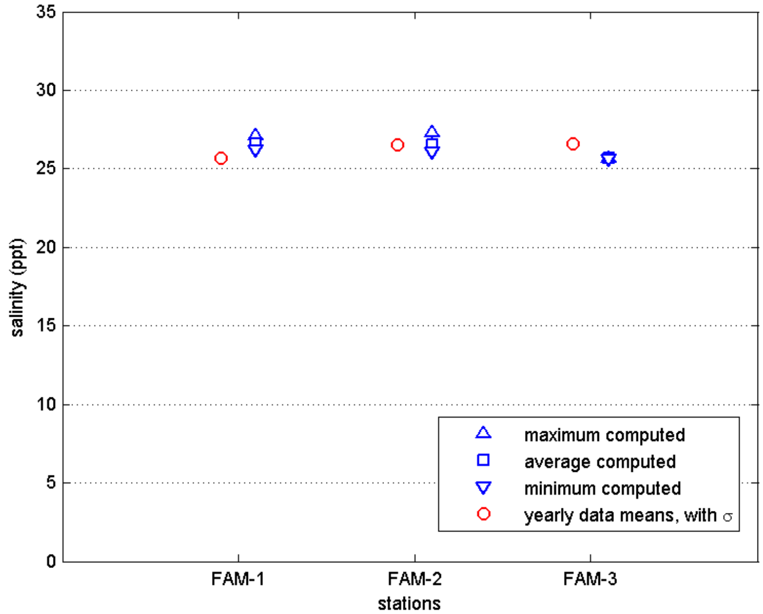


Figure VI-5. Comparison of measured and calibrated model output at stations in Farm Pond. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the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

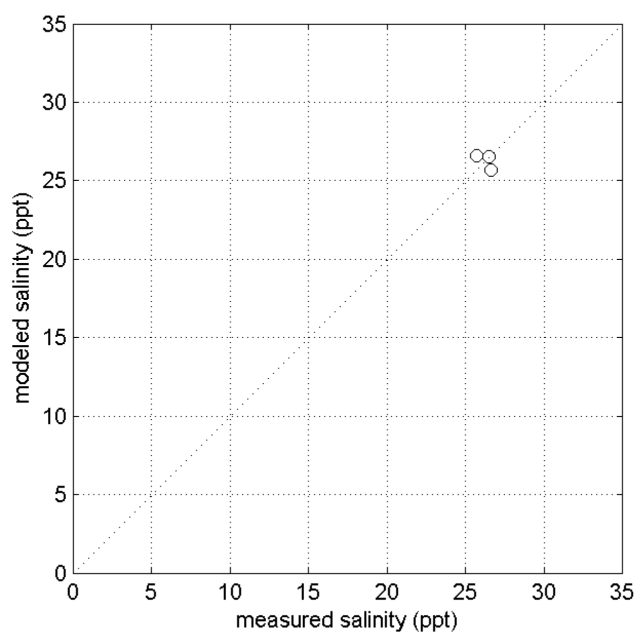


Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. Computed RMS error for this model verification run is 0.8 ppt.

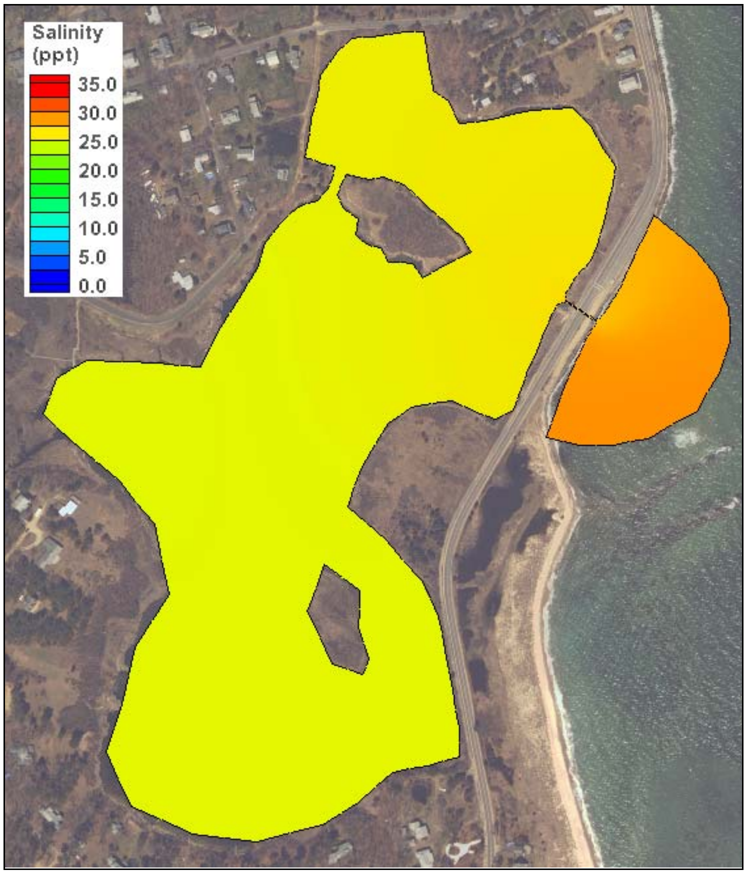


Figure VI-7. Contour Plot of average modeled salinity (ppt) in the Farm Pond system.

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 Farm Pond system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	Build-out (kg/day)	build-out % change	no load (kg/day)	no load % change
Farm Pond System Total	5.970	7.151	+19.8%	0.233	-96.1%

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 *vise versa*.

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Table VI-5. **Build-out** scenario sub-embayment and surface water loads used for total nitrogen modeling of the Farm Pond system, with total watershed N loads, atmospheric N loads, and benthic flux.			
sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Farm Pond System Total	7.151	0.490	-0.991

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 within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios. For build-out, the increase in modeled TN concentrations increase approximately 20% compared to background across the pond. A contour plot showing average TN concentrations throughout the river system is presented in Figure VI-8 for the model of build-out loading.

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 VI-6. The percent change *P* over background presented in this table is calculated as:

$$P = (N_{threshold} - N_{present}) / (N_{present} - N_{background})$$

where N is the nitrogen concentration at the indicated monitoring station for present and threshold conditions, and also in Nantucket Sound (background).

Table VI-6. Comparison of model average total N concentrations from present loading and the **build-out scenario**, with percent change over background in Nantucket Sound (0.294 mg/L), for the Farm Pond system.				
Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out (mg/L)	% change
North Basin	FAM-1	0.496	0.535	+19.2%
Mid Pond	FAM-2	0.480	0.517	+19.4%
South Basin	FAM-3	0.508	0.550	+19.7%

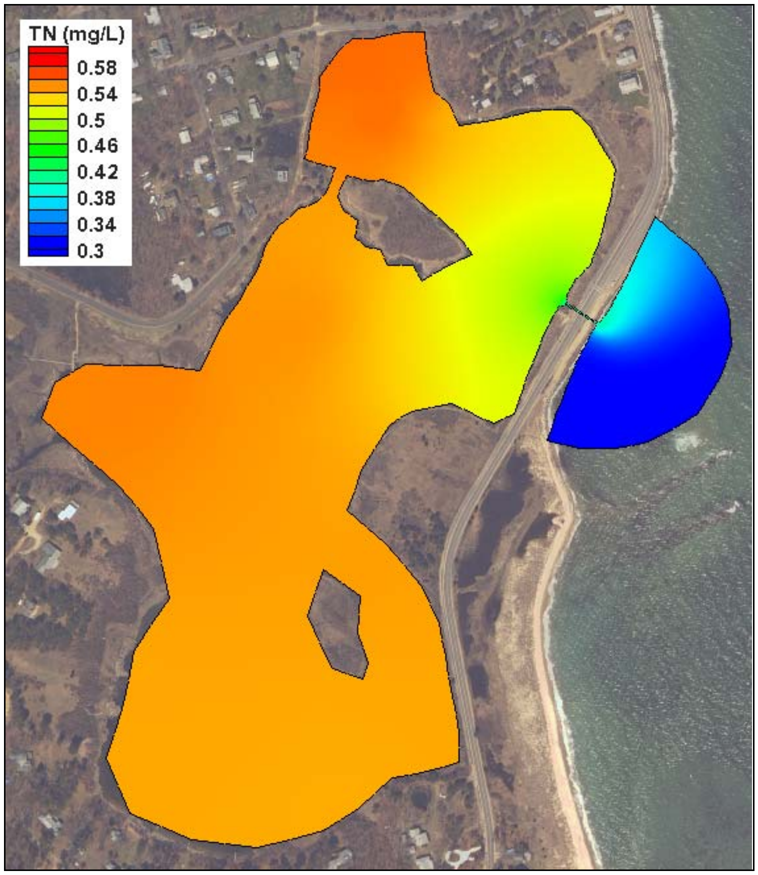


Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Farm Pond system, for projected build-out scenario loading conditions.

VI.2.6.2 No Anthropogenic Load

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

Table VI-7. "**No anthropogenic loading**" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Farm Pond system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
System Total	0.23	0.49	-0.41

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations at each monitoring station. Again, total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was large, with all areas of the system experiencing reductions greater than 93%, compared to the background concentration of 0.294 in Nantucket Sound. 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 Nantucket Sound (0.294 mg/L), for the Farm Pond system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	no-load (mg/L)	% change
North Basin	FAM-1	0.496	0.307	-93.4%
Mid Pond	FAM-2	0.480	0.305	-94.1%
South Basin	FAM-3	0.508	0.304	-95.4%

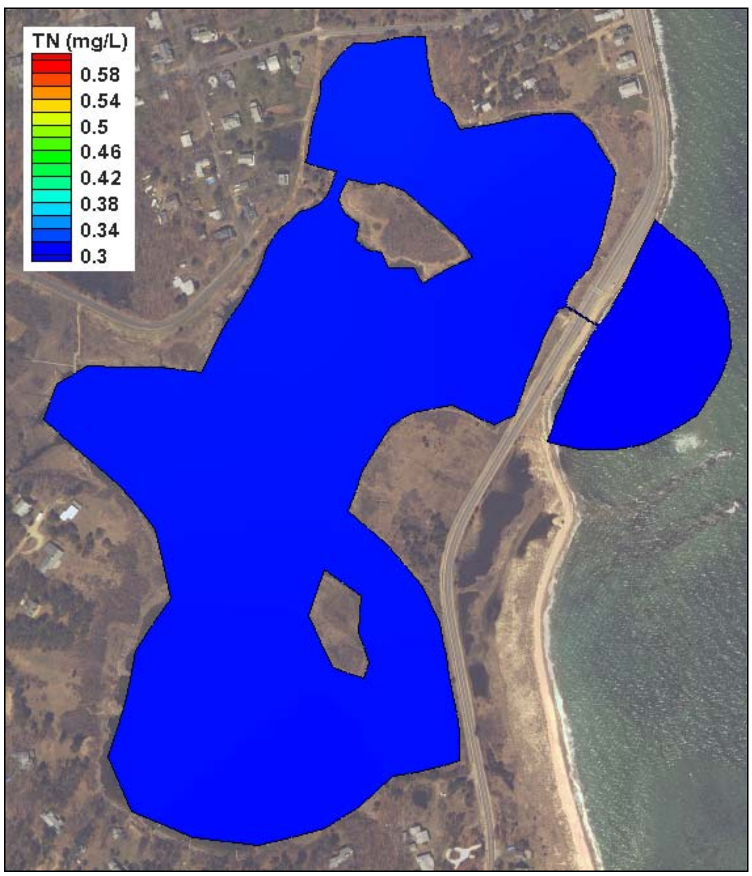


Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in Farm Pond, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll-*a*, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Farm Pond embayment system in the Town of Oak Bluffs, MA, our assessment is based upon data from the water quality monitoring database developed by the Martha's Vineyard Commission and their partners and surveys of eelgrass distribution, benthic animal communities and sediment characteristics, and dissolved oxygen records conducted during the summer and fall of 2006. These data form the basis of an assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for this system (Chapter VIII). 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 the low nitrogen waters of Vineyard Sound. Farm Pond has increasing nitrogen loading from its watershed from shifting land-uses and clearly has restricted tidal exchange. Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs.

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen threshold determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll-*a* (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed an autonomous dissolved oxygen sensor in Farm Pond at a location that would be representative of the dissolved oxygen condition at the critical location in the system, namely the southern basin slightly removed from the influence of inflowing waters from Vineyard Sound. The dissolved oxygen mooring was deployed to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen overloading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Farm Pond system was conducted for comparison to historic records (MassDEP Eelgrass Mapping Program, C. Costello and Martha's Vineyard Commission, 1998). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Analysis of inorganic N/P molar ratios within the water column of Farm Pond support this contention that nitrogen is the nutrient to be managed, as the ratio in the Pond (6) is far below the Redfield Ratio value (16) indicating that nitrogen additions will increase phytoplankton production in this system. Within the Farm Pond system, temporal changes in eelgrass distribution provided a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet) in nutrient enrichment.

In areas that do not support eelgrass beds, benthic animal indicators were used to assess the level of habitat health from “healthy” (low organic matter loading, high D.O.) to “highly stressed” (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of their habitat. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life history information on the species and a wide variety of field studies within southeastern Massachusetts waters, including the Wild Harbor oil spill, benthic population studies in Buzzards Bay (Woods Hole Oceanographic Institution) and New Bedford (SMAST), 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. Massachusetts State Water Quality Classification indicates that SA (high quality) waters be able to maintain oxygen levels above 6 mg L-1. The tidal waters of the Farm Pond embayment 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 and that it is the designated water quality that is the target of TMDL's generated under the U.S. Clean Water Act. It is through the MEP and TMDL processes that site specific management targets are developed and under the Town's CWMP that management alternatives are designed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, an autonomously recording oxygen sensor was moored 30 cm above the embayment bottom within the key region of the Farm Pond system (Figure VII-2). The dissolved oxygen sensor (YSI 6600) was first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the Farm Pond system was collected during the summer of 2006.

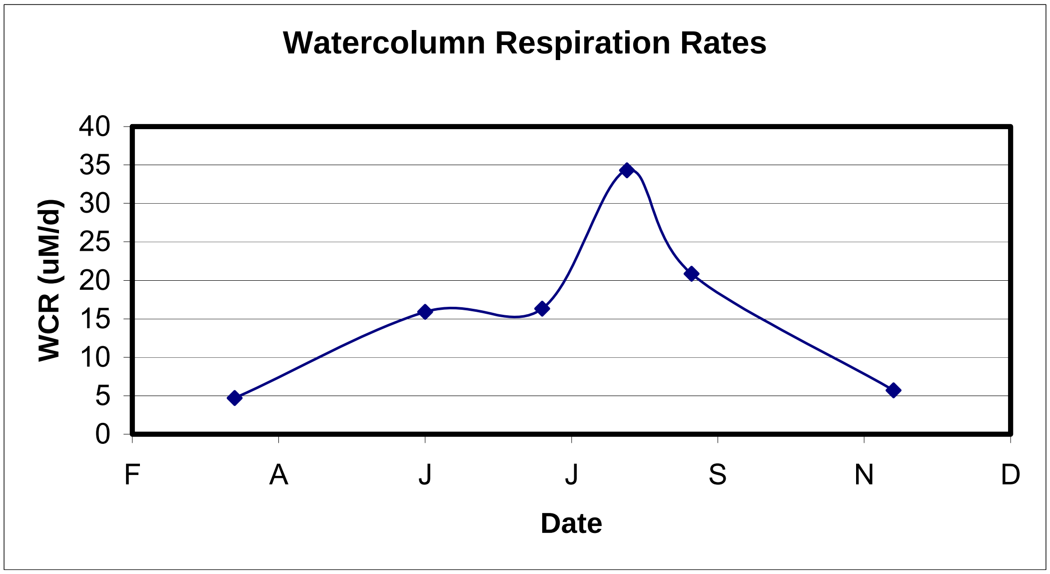


Figure VII-1. Example of typical average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System, Cape Cod (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter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

Similar to other embayments in southeastern Massachusetts, the Farm Pond system evaluated in this assessment showed high frequency variation, apparently related to diurnal and sometimes tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration at each mooring site, underscores the need for continuous monitoring within these systems.

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 43 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate significantly nutrient enriched waters within the southern basin of Farm Pond (Figures VII-3 through VII-4). The oxygen data are consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-*a*. The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follows the spatial pattern of total nitrogen levels in this system (Chapter VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

The oxygen record for Farm Pond shows that the inner most basin in the southern portion of the system has large daily oxygen excursions, indicative of nitrogen enrichment. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration indicates that the southern portion of the system which is tidally restricted is nitrogen enriched. Measured dissolved oxygen depletion indicates that the southern portion of Farm Pond shows moderate to significant oxygen stress. The embayment specific results are as follows:

Farm Pond DO/CHLA Mooring (Figures VII-3 and VII-4):

The Farm Pond instrument mooring was located at the southern end of the system away from the inlet connecting Farm Pond to waters from Vineyard Sound. Large daily excursions in oxygen levels were observed at this location, ranging from levels more than twice air equilibration to hypoxic conditions where levels frequently decline to 4 mg L^{-1} and infrequently to <2 mg L^{-1} (Figure VII-3, Table VII-1). The organic enrichment of the system is demonstrated by the high rates of photosynthesis (carbon fixation) and the rapid and significant declines in oxygen after sunset stemming from respiration.

Oxygen levels regularly exceeded 15 mg L^{-1} and periodically exceeded 20 mg L^{-1}. These high oxygen levels are likely the result of the combined effects of photosynthesis by eelgrass (and its epiphytes) and moderately high phytoplankton biomass and relatively quiescent waters. Over the 43 day deployment there appear to be multiple phytoplankton blooms where chlorophyll-*a* increased to 10-15 ug L^{-1}. While the periodic hypoxia is indicative of moderate to significant habitat impairment, the chlorophyll-*a* levels, while elevated, were indicative of only moderate nitrogen enrichment (mooring average 7.5 ug L^{-1} and multi-year summer average, 6.7 ug L^{-1}) and with chlorophyll-*a* exceeding the 10 ug L^{-1} benchmark 15% of the time (Table VII-2, Figure VII-4). Average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

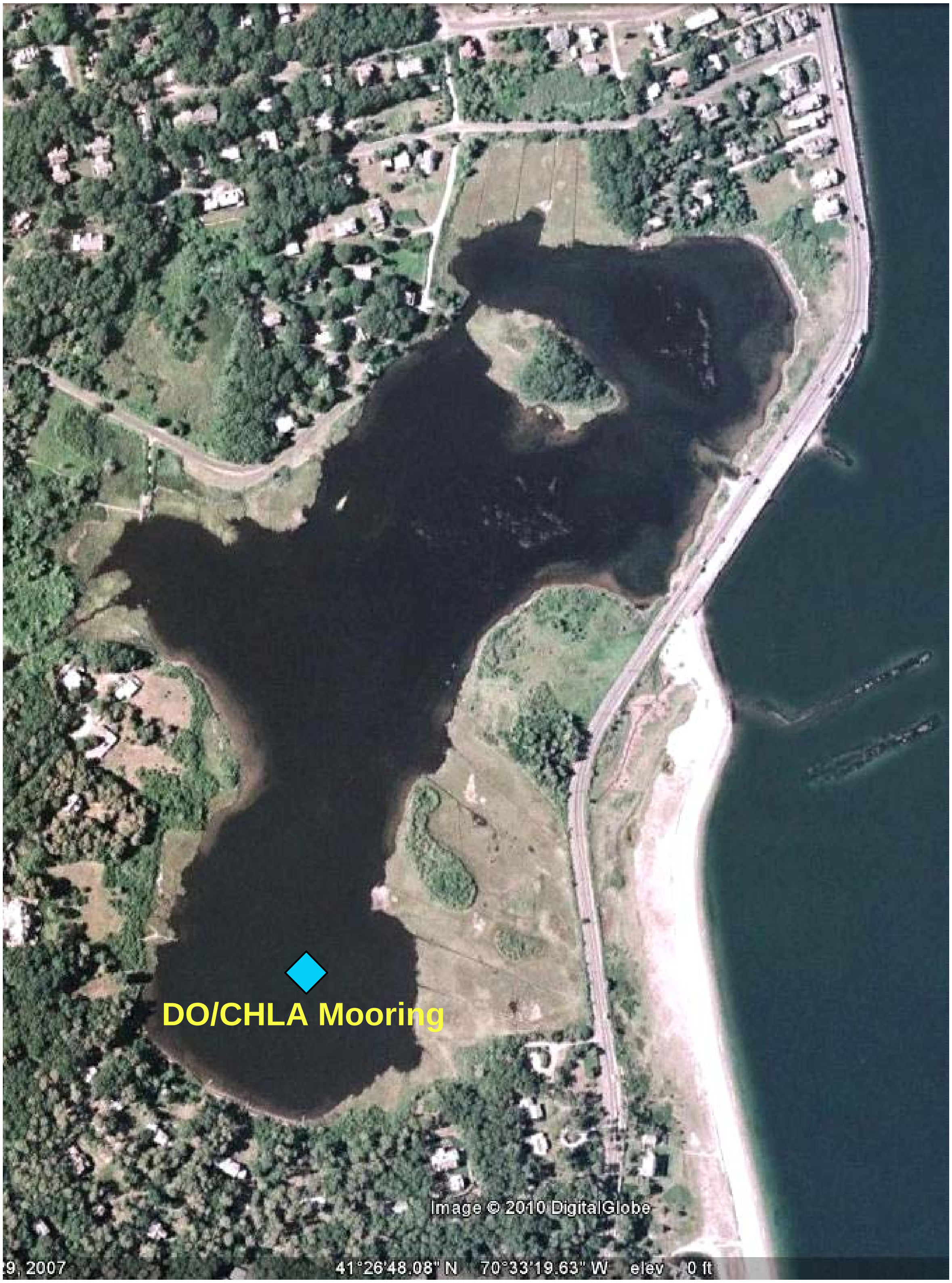


Figure VII-2. Aerial Photograph of the Farm Pond system in the Towns of Oak Bluffs showing the location of the continuously recording Dissolved Oxygen / Chlorophyll-*a* sensors deployed during the Summer of 2006.

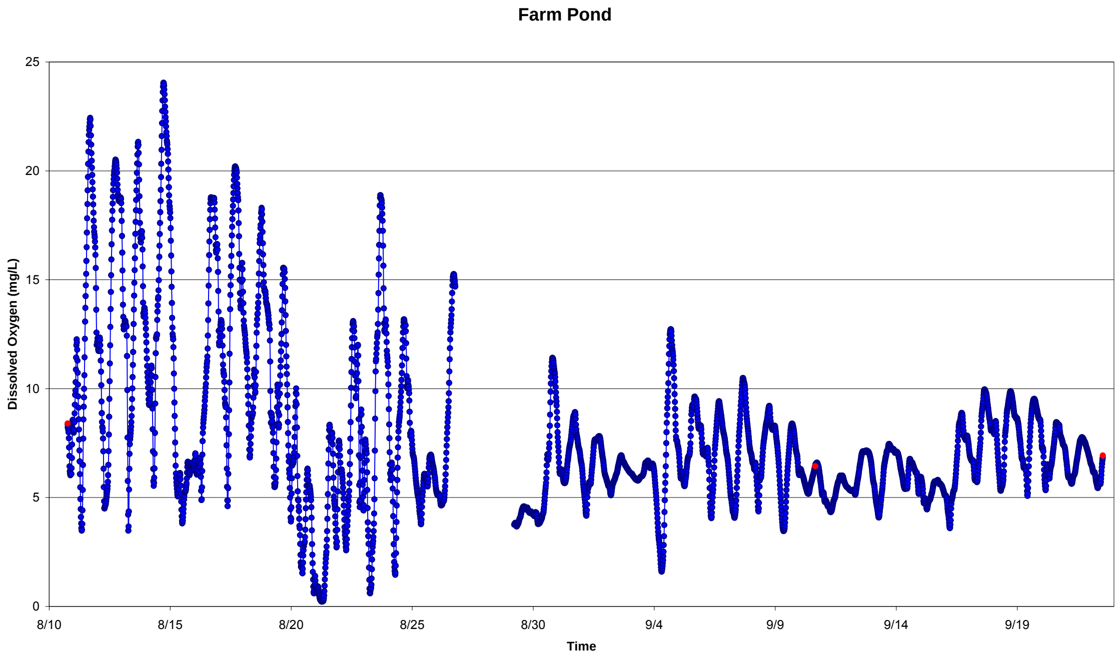


Figure VII-3. Bottom water record of dissolved oxygen at the Farm Pond station, Summer 2006. Calibration samples represented as red dots.

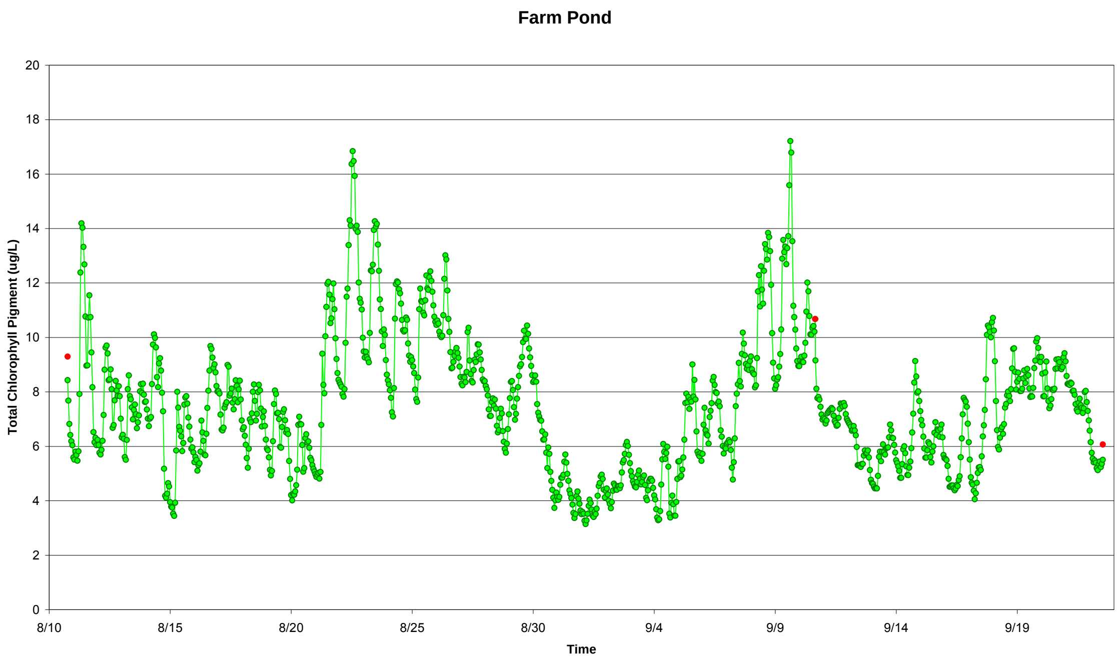


Figure VII-4. Bottom water record of Chlorophyll-*a* in the Farm Pond station, Summer 2006. Calibration samples represented as red dots.

Table VII-1. Days and percent of time during deployment of *in situ* sensors that bottom water oxygen levels were below various benchmark oxygen levels within the Farm Pond embayment system.

Embayment System	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)
Farm Pond	**8/10/2006**	**9/22/2006**	**42.8**	**33%**	**15%**	**6%**	**3%**
			Mean	0.29	0.23	0.16	0.20
			Min	0.03	0.02	0.01	0.04
			Max	1.59	1.26	0.65	0.61
			S.D.	0.31	0.25	0.16	0.20

Table VII-2. Duration (days and % of deployment time) that chlorophyll-*a* levels exceed various benchmark levels within the Farm Pond 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.

Embayment System	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Farm Pond	**8/10/2006**	**9/22/2006**	**42.8**	**84%**	**15%**	**0.7%**	**0.0%**	**0.0%**
Mean Chl Value = 7.5 ug/L			**Mean**	2.01	0.37	0.15	N/A	N/A
			Min	0.04	0.04	0.13	0.00	0.00
			Max	9.54	1.29	0.17	0.00	0.00
			S.D.	2.65	0.33	0.03	N/A	N/A

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Farm Pond eelgrass distribution data were generated by Martha's Vineyard Commission working with the Town of Oak Bluffs (1997 and 2006 maps) with validation field surveys by SMAST/MEP Technical Team members during the conduct of MEP related field work in 2006 (see Chapter 2). The MassDEP Eelgrass Mapping Program assembled this data into its standard format for use in the MEP analysis. Additional analysis by the MassDEP Eelgrass Mapping Program of available aerial photos from 1951 was used to try to reconstruct the eelgrass distribution prior to any substantial development of the watershed. The Farm Pond 1951 aerial imagery was found to be inadequate for quantitative photo-interpretation of historic eelgrass distribution. As such the eelgrass analysis is based solely on survey work completed in 1997 and 2006 (Figure VII-6 and VII-7). The primary use of the data are to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1997 to 2006 (Figure VII-11); the period in which watershed nitrogen loading significantly increased to its present level. This temporal information can be used to determine the stability of the eelgrass community.

At present, eelgrass exists across a relatively large portion of the system, particularly in the south basin (Figure VII-5). The results of the 2006 survey was confirmed by multiple MEP staff conducting infaunal animal and sediment sampling and mooring studies in the summer and fall of 2006. The slight decline in the aerial distribution of eelgrass beds in Farm Pond from 1997 to 2006 is expected given the observed nitrogen levels and resulting chlorophyll-*a* and dissolved oxygen depletions within this embayment system.

The condition of the eelgrass bed observed in 2006 by SMAST/MEP Technical Team members is also consistent with the observed moderate level of nutrient enrichment across the three water quality monitoring stations that represent nutrient levels throughout the pond. Field observations by SCUBA diver of the eelgrass beds during the sediment survey indicated high coverage by epiphytes in some areas and only sparse patchy eelgrass colonization within the north basin.

The amounts of epiphytic growth in different areas of Farm Pond varied the most between sample sites #5 and #6 (Figure 6), with an epiphyte biomass of 2.9 g/m^2 up to 8.5 g/m^2, respectively, with similar organisms found on both (Wilcox, 1998). Samples 1, 2, 3 and 4 all exhibited levels in between these numbers. At the time of the 1998 survey, relative to specific eelgrass sample locations in the pond, no pattern is evident as to one region of the pond having a greater amount of epiphytes than another, supporting the possibility that at the time, the pond was fairly uniform in its characteristics (i.e. nutrient levels, light penetration, depth, etc.). At sample sites 1 through 4 and 6, algae (probably a mix of diatom chains and algae) dominated the epiphyte population while at site 5 *Spirobis*, sea squirts and algae were found. As a percentage of the dry weight of the eelgrass blades, in 1998 the epiphytes ranged from 13 to 39 percent, implying a moderate level of growth (Wilcox, 1998). However, healthy eelgrass stands generally have very low epiphyte growth.

The occurrence of eelgrass in both the north versus south basins is consistent with the shallow nature of the pond (basins ~1 m), moderate chlorophyll-*a* levels and resulting light penetration to the bottom, as seen in the Secchi data (disk could be seen on the bottom). The epiphytes and patches of drift algae are likely related to the lack of full colonization of the pond basin by eelgrass and the possible recent decline in coverage. Again it must be stressed that nitrogen enrichment and resulting decline in habitat quality is linked both to increasing nitrogen inputs and/or decreasing tidal exchange rates. Improvements in either factor will result in improved habitat quality.

Total nitrogen levels (TN) within Farm Pond with its moderately stressed but relatively stable eelgrass beds has a mean summer-time level of 0.516-0.530 mg N L^{-1} as determined from the water quality monitoring program (Chapter VI). These TN levels are higher than generally found in high quality eelgrass habitat such as within deeper systems ($\geq$2 m) like Stage Harbor (0.38 mg L^{-1}) or West Falmouth Harbor (0.35 mg L^{-1}), but were found to decline in the lower basin of Waquoit Bay at a slightly higher TN of 0.395 mg L^{-1}. In shallow systems like Farm Pond, with eelgrass generally at <1 m depth, eelgrass beds are sustainable at higher TN (higher chlorophyll-*a*) levels than in deeper waters, because of the "thinner" water column that light has to pass through to support eelgrass growth (less water to penetrate). At similar depths in Bournes Pond, eelgrass can be still be found (although heavy with epiphytes) at the mouth of the upper tributary at a tidally averaged TN concentration of 0.481 mg TN L^{-1}, while the more stable beds in the lower region of Israel's Cove have at a tidally averaged TN of 0.429 mg TN L^{-1}. It should be added that eelgrass can persist at nitrogen levels that are non-supportive of healthy beds, and eelgrass within Hamblin Pond persisted at a high TN level (0.5 mg L-1) after eelgrass within the central portion of Waquoit Bay had disappeared, but the 0.5 mg N L-1 TN level was associated with a few diminishing small patches of sparse eelgrass and is not supportive of high quality habitat. All of the eelgrass information for Farm Pond indicates that the eelgrass habitat is generally moderately impaired with likely significant impairment in the north basin.

Other key water quality indicators, dissolved oxygen and chlorophyll-*a*, show similar levels of moderate enrichment with periodic oxygen depletions frequently to 6-4 mg L^{-1} and chlorophyll-*a* levels averaging 7 ug L^{-1} with periodic blooms in the 10-15 ug L^{-1} range. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, the eelgrass with epiphytes and significantly impaired eelgrass habitat in the north basins is to be expected.

It is not possible to determine quantitative short- and long-term rates of change in eelgrass coverage from the mapping data, since there is only limited temporal data. However, it is possible to utilize the 1997 coverage data as an indication of the minimum area of eelgrass habitat that might be recovered (on the order of 2.5 acres) if nitrogen management alternatives were implemented (Table VII-3). However, it is more likely that recovery of the habitat in the north basins would occur simultaneously increasing the recovered acreage to ~5 acres or an increase of ~30% of the existing bed area (16.8 acres). It should be noted more importantly, that the health of the eelgrass that still exists in Farm Pond would improve significantly with an increase in density, reduction in epiphytes and drift algae and increase in associated fauna. Additionally, restoration of this eelgrass habitat will necessarily result in restoration of other resources throughout the Farm Pond Embayment System. With a reduction in nitrogen loading to Farm Pond benthic infaunal habitat would be restored with an increase in shellfish habitat and shift toward larger longer lived deep burrowing organisms (see below discussion on benthic infaunal community survey).

Other factors which influence eelgrass bed loss in embayments can also be at play in the Farm Pond Embayment System, though the recent loss appears completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, as the system does not support any permanent boat mooring area. While pier construction can cause impacts to eelgrass beds, there are few if any significant piers on the shores of Farm Pond. On the other hand, boating pressure or small scale shell fishing may be adding additional stress in nutrient enriched areas, but it does not seem to be the overarching factor, especially given structure of this basin, the limited access, and the lack of navigable water.

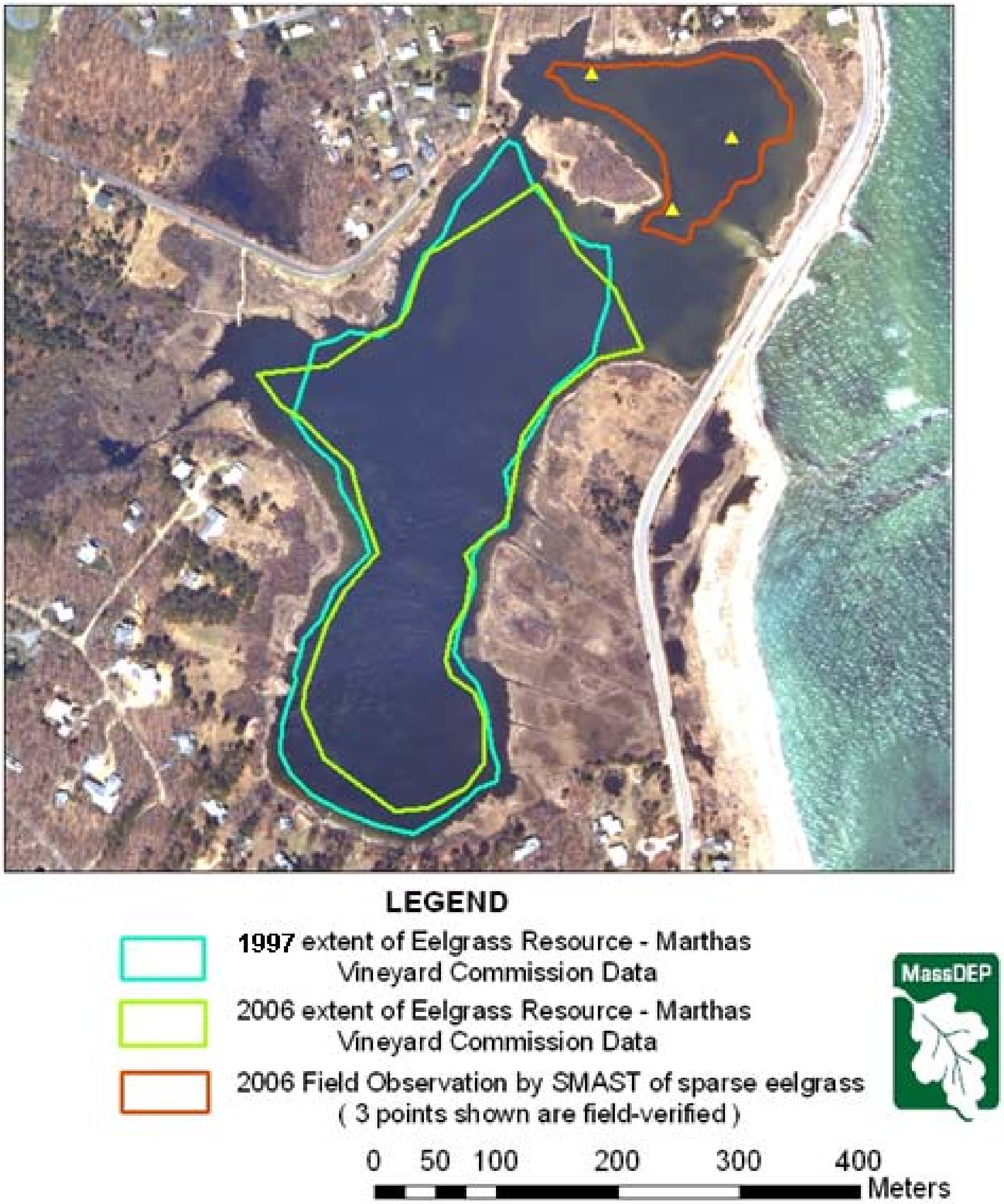


Figure VII-5. Eelgrass bed distribution within the Farm Pond System. Beds delineated in 1997 are circumscribed by the light blue outline, with 2008 outlined in green (map from the MassDEP Eelgrass Mapping Program). Sparse eelgrass coverage was observed in 2006 in SMAST-MEP surveys and was also noted by the Town of Oak Bluffs Shellfish Constable in that same year.

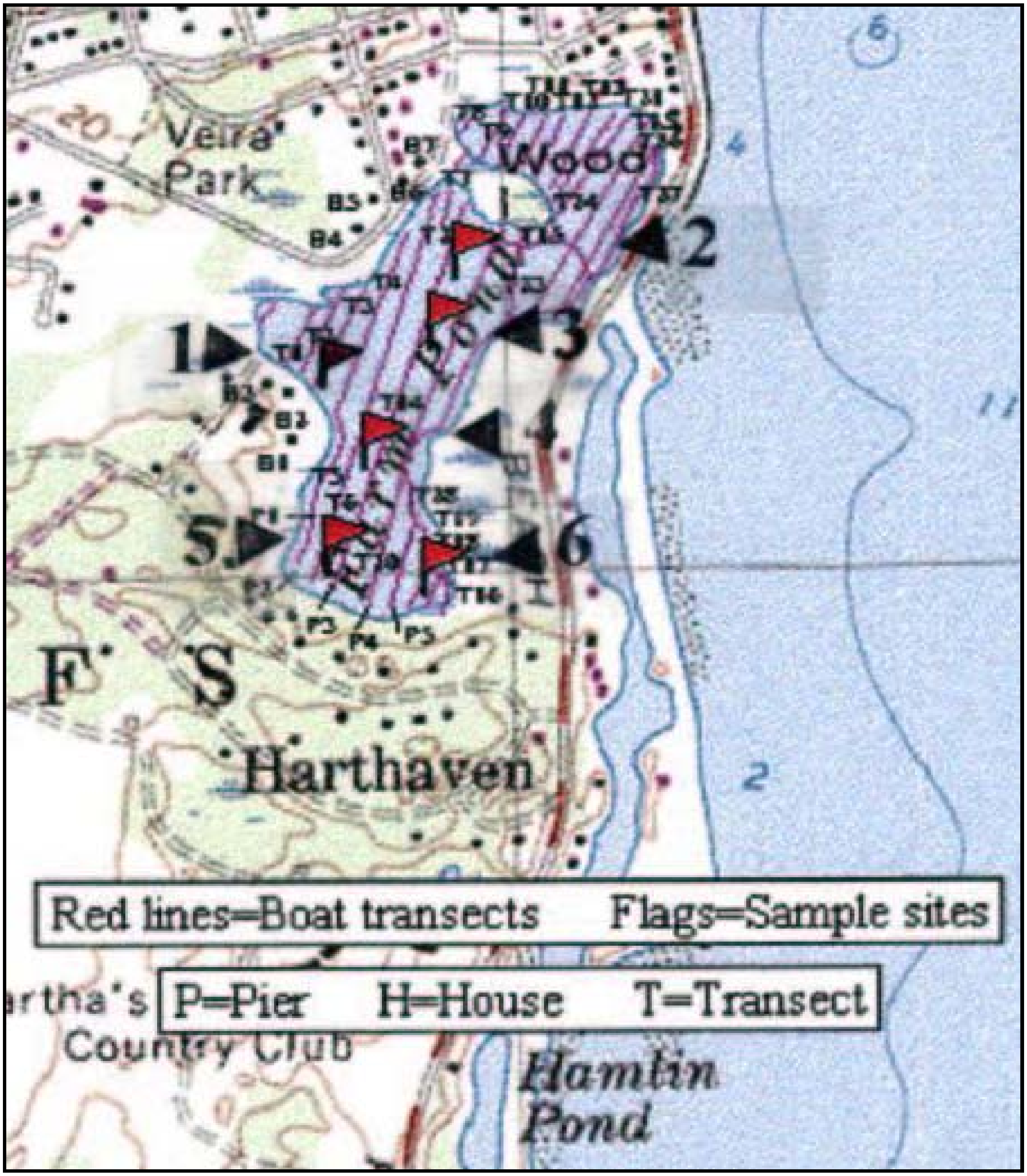


Figure VII-6. Map of eelgrass survey transects and sampling sites Farm Pond as conducted by the Martha's Vineyard Commission in 1998.

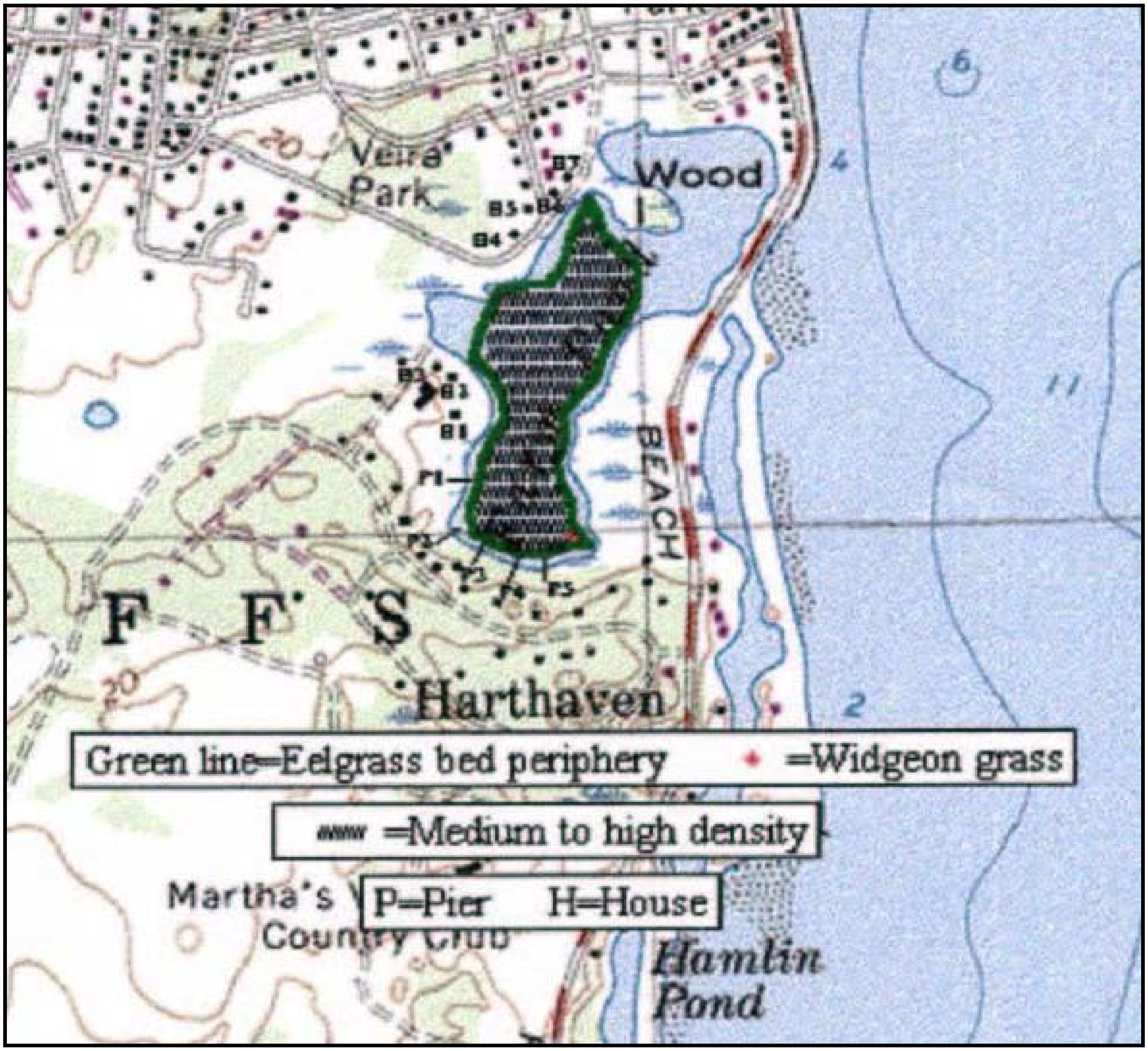


Figure VII-7. Map of eelgrass distribution in Farm Pond as completed by the Martha's Vineyard Commission in 1998.

Table VII-4. Temporal changes in eelgrass coverage in the Farm Pond Embayment System within the Towns of Oak Bluffs 1997 to 2001 (MassDEP, C. Costello).

Embayment	1951 (acres)	1997 (acres)	2006 (acres)	Percent Difference (1995 to 2001)
Farm Pond	NA	19.21	16.82	**12%**

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 4 locations within the Farm Pond Embayment System (Figure VII-8), with replicate assays at each site. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the presence of significant quantities of epiphytes and potential loss of eelgrass from 1997 to 2006, most of Farm Pond is moderately impaired by nutrient overloading, with and indication or higher impairment in the northern basin. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

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

Overall, the Infauna Survey indicated that the basins comprising Farm Pond are presently supporting impaired benthic infaunal habitat (Table VII-5). Infaunal habitat within the northern basin is severely degraded, based upon the very low numbers of animals present (~20 per sample) and few species (5 per sample). The southern basin, while supporting a higher habitat quality, is still significantly impaired. The designation of significant impairment stems from the presence of higher numbers of individuals and species, but a community dominated by stress tolerant species indicative of high levels of organic enrichment. About 50% of the total community consisted of a single species, *Capitella capitata*, generally found in embayments with high organic matter deposition and poor habitat quality. In contrast, high quality infaunal habitat is supportive of much higher numbers of individuals and species with high Diversity and Evenness. For example, the outer stations within Lewis Bay in Barnstable currently support high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Evenness (0.74). Equally important the community is not consistent with nutrient enrichment and is composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms.

There is generally an increase in the overall level of habitat impairment moving from south to north within Farm Pond. This trend is seen both in eelgrass and infaunal habitat quality. The observed infaunal communities are consistent with the frequent summertime hypoxia in bottom waters and the organic rich soft sediments with only a thin oxidized surface layer. The observed nitrogen levels in Farm Pond waters (0.516-0.530 mg N L^{-1}) presently exceed thresholds for high quality benthic habitat, although the observed degree of impairment would generally be seen at higher nitrogen levels. However, the results are clear and with little variation within sites. Classification of habitat quality necessarily included the structure of the estuarine basin, specifically that it is fully representative of a tidal embayment, as opposed to a tidal river or salt marsh basin. Based upon this analysis it is clear that the embayment basins are presently supporting significantly impaired to severely degraded benthic habitat whose proximate cause is organic matter enrichment and hypoxia and whose ultimate cause in nitrogen enrichment. Since Farm Pond does not exhibit strong horizontal gradients in water quality parameters and since the system presently has impaired eelgrass habitat, lowering the nitrogen to improve eelgrass habitat, primarily in the southern basin, will also be sufficient to restore infaunal animal habitat so no separate nitrogen threshold is required for this system for infauna.

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. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the propagation of shellfish (Figure VII-9). As is the case with some systems on Cape Cod, all of the enclosed waters of Farm Pond are classified as prohibited for the taking of shellfish during any given season of the year, indicating the system is clearly impaired relative to the taking of shellfish. This is likely due to bacterial concerns which would be a result of both human activity (septic systems in the watershed) as well as natural fauna. Nevertheless, the Farm Pond system has also been classified as supportive of specific shellfish communities (Figure VII-10). The major shellfish species with potential habitat within the Farm Pond Estuary are soft shell clams (*Mya*) and quahogs (*Mercenaria*) extending essentially along the shallow waters at the edge of the pond forming a ring most of the water around the pond. It should be noted that the observed pattern of shellfish growing area is consistent with the observed organic rich sediments within the basins and the hypoxia in the bottom waters, the "ring" encompasses the shallows where hypoxia is less frequent and severe. Improving benthic animal habitat quality should also expand the shellfish growing area within this system.

Figure VII-8. Aerial photograph of the Farm Pond system showing location of benthic infaunal sampling stations (red symbol).

Table VII-5. Benthic infaunal community data for the Farm Pond embayment system. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m2). Stations refer to map in Figure VII-8, (N) is the number of samples per site.

Site	Total Actual # Species	Total Actual # Individuals	Species Calculated @ 75 Indiv.	Weiner Diversity (H')	Evenness (E)
Farm Pond North Basin					
FRM-6/7	5	21	--[1]	1.95	0.90
Farm Pond South Basin					
FRM-4	4	37	--[1]	1.49	0.74
FRM-3	11	230	9	2.04	0.59
FRM-1	8	251	7	1.90	0.63

1- too few individuals extant in field sample to support this calculation.
2- all values are the average of replicate samples

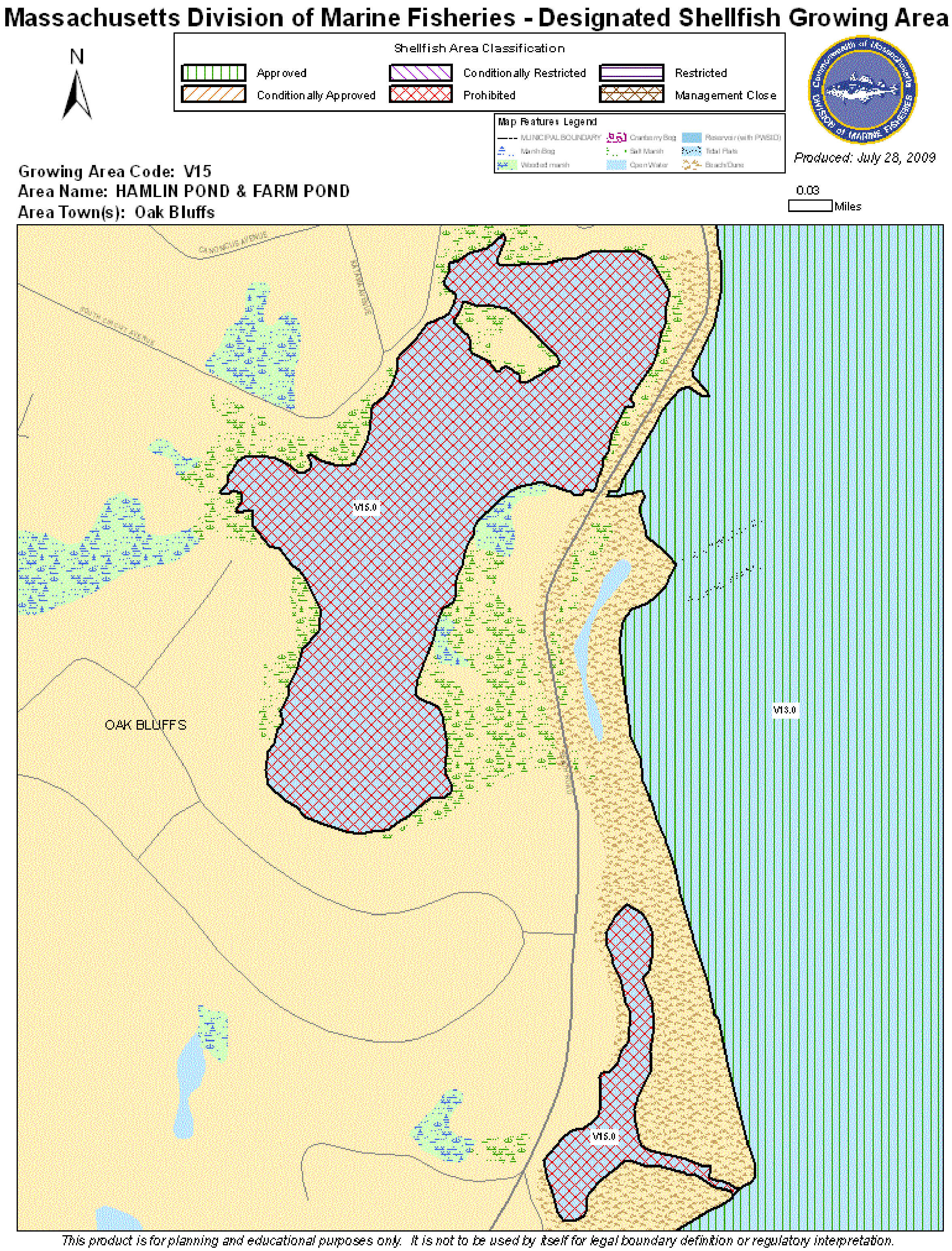


Figure VII-9. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

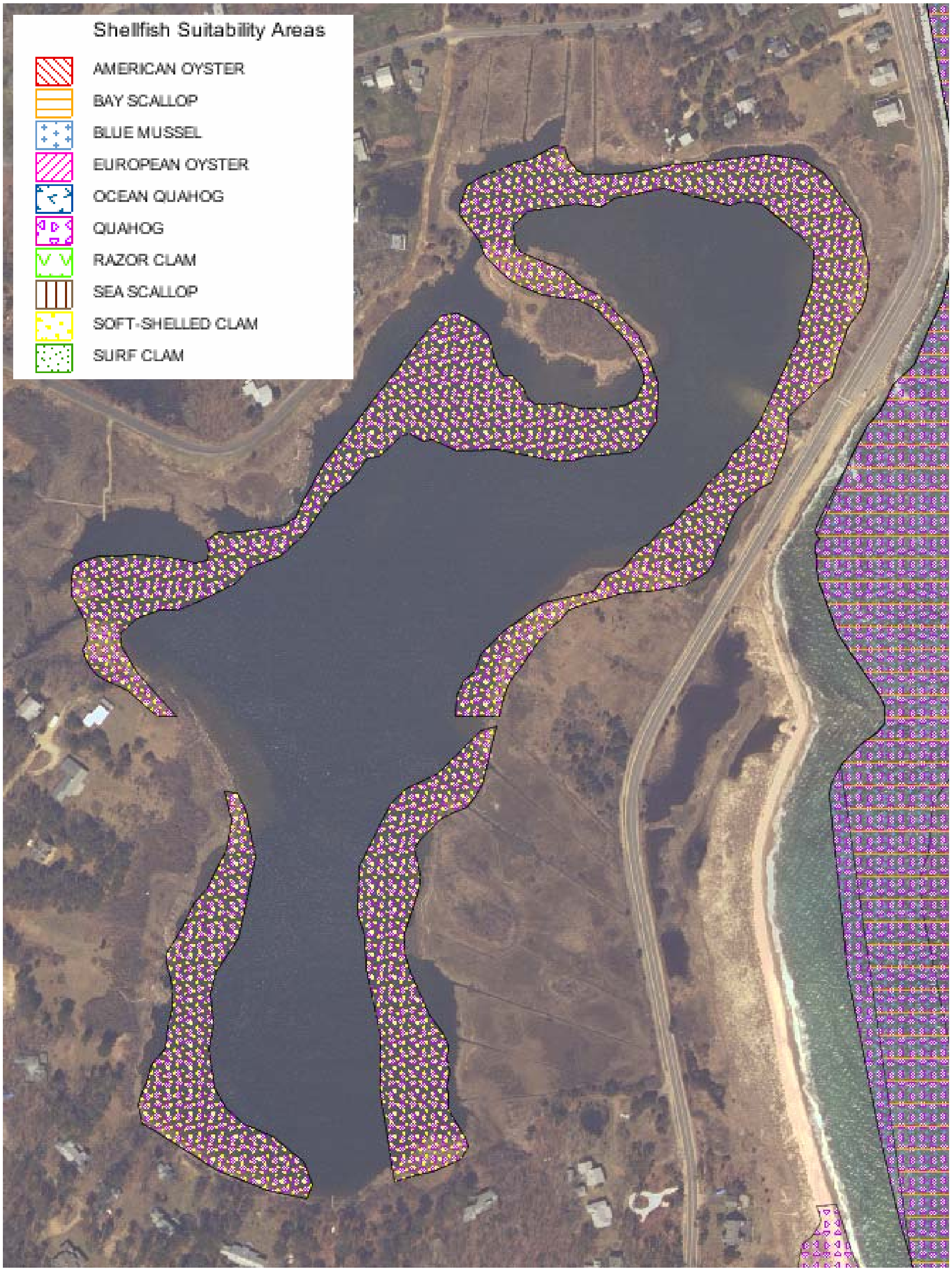


Figure VII-10. Location of shellfish suitability areas within the Farm Pond estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

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

The Farm Pond Embayment System is a simple estuary formed as a lagoon behind an active barrier beach. It is composed of a single functional type of basin: a single central basin without major stream inflow or tributary sub-embayments. Each type of functional component (salt marsh basin, embayment, tidal river, drown kettle 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 type of basin and the ability to support eelgrass beds and the types of infaunal communities that they support. At present, the Farm Pond Estuary is showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Chapter VII). For the purposes of this analysis Farm Pond was separated into a northern basin roughly above Woody Island and a larger southern basin south of Woody Island.

Overall, the system is showing some nitrogen related habitat impairment throughout the tidal reach. While there is little horizontal gradient in water quality parameters within Farm Pond due to horizontal mixing, there is a clear gradient of declining habitat quality moving from south to north. The north basin is a significantly impaired basin relative to eelgrass. Although the basin presently supports sparse eelgrass coverage, the sparse patchy coverage indicates significant impairment. In contrast, the relatively dense eelgrass beds in the southern basin which appear to be declining only slightly are moderately impaired, the moderate impairment designation stems from the likely reduction in coverage and the observed moderate density of epiphytes on the eelgrass blades. Similarly, the basins have impaired infaunal habitat, with severely degraded habitat in the northern basin which is virtually devoid of animals and significantly degraded habitat in the southern basin which has moderate numbers of animals, but is dominated (50%) by the organic enrichment tolerant species, *Capitella capitata*. These levels of impairment are also reflected in the observed periodic hypoxia, phytoplankton blooms and nitrogen enrichment (Table VIII-1).

Eelgrass: The distribution of eelgrass throughout the Farm Pond Estuary is consistent with the observed nitrogen, the chlorophyll-*a* levels and the systems function as a shallow open water embayment with restricted tidal exchange. At a lower level of nitrogen enrichment, it is expected that Farm Pond would have improved water clarity and oxygen status resulting in improved habitat for eelgrass and infauna. At present, eelgrass exists across a relatively large portion of the system, particularly in the south basin (Figure VII-5). The apparent slight decline in the aerial distribution of eelgrass beds in Farm Pond from 1997 to 2006 is expected given the observed nitrogen levels and resulting chlorophyll-*a* and dissolved oxygen depletions within this embayment system.

The condition of the eelgrass bed observed in 2006 by SMAST/MEP Technical Team members is also consistent with the observed moderate level of nutrient enrichment across the three water quality monitoring stations that represent nutrient levels throughout the pond. Field observations by SCUBA diver of the eelgrass beds during the sediment survey indicated high coverage by epiphytes in some areas and only sparse patchy eelgrass colonization within the north basin. These observations mirrored measured epiphyte growth by the MV Commission and observations of sparse eelgrass in the north basin in 2006 by the Town of Oak Bluffs Shellfish Department.

The occurrence of eelgrass in both the north versus south basins is consistent with the shallow nature of the pond (basins ~1 m), moderate chlorophyll-*a* levels and resulting light penetration to the bottom, as seen in the Secchi data (disk could be seen on the bottom). The epiphytes and patches of drift algae are likely related to the lack of full colonization of the pond basin by eelgrass and the possible recent decline in coverage. Again it must be stressed that nitrogen enrichment and resulting decline in habitat quality is linked both to increasing nitrogen inputs and/or decreasing tidal exchange rates. Improvements in either factor will result in improved habitat quality.

Total nitrogen levels (TN) within Farm Pond, with its moderately stressed but relatively stable eelgrass beds, showed summer-time tidally averaged levels in the 0.48 - 0.51 mg N L^{-1} range as determined from the validated water quality model (Chapter VI). Typically eelgrass beds exist at lower nitrogen levels (0.35 - 0.45 mg N L^{-1}) than presently found in this system. These TN levels are significantly higher than generally found in high quality eelgrass habitat within deeper basins ($\geq$2 m) like Stage Harbor (0.38 mg L^{-1}) or West Falmouth Harbor (0.35 mg L^{-1}). In these deeper waters eelgrass has been found to decline at average TN concentrations of 0.395 mg L^{-1} (e.g. lower basin of Waquoit Bay). However, Farm Pond is a shallow water basin with depths generally less than 1 meter. In shallow systems like Farm Pond, eelgrass beds are sustainable at higher TN (higher chlorophyll-*a*) levels than in deeper waters, because of the "thinner" water column that light has to pass through to support eelgrass growth (less water to penetrate). In systems analogous to Farm Pond, for example at similar depths in Bournes Pond, eelgrass can still be found (although heavy with epiphytes) at the mouth of the upper tributary at a tidally averaged TN concentration of 0.481 mg TN L^{-1}, while the more stable beds in the lower region of Israel's Cove have at a tidally averaged TN of 0.429 mg TN L^{-1}.

It should be stressed that eelgrass can persist at nitrogen levels that are non-supportive of healthy beds, and eelgrass within Hamblin Pond persisted at a high TN level (0.5 mg L-1) after eelgrass within the central portion of Waquoit Bay had disappeared, but the 0.5 mg N L-1 TN level was associated with a few diminishing small patches of eelgrass and was not supportive of high quality habitat. The levels of TN and quality of the eelgrass habitat are comparable to similar shallow systems on Cape Cod, where at these TN levels the eelgrass is stressed, has epiphytes and is just beyond its tolerance limit.

Other key water quality indicators, dissolved oxygen and chlorophyll-*a* are consistent with the eelgrass and infaunal data, with periodic oxygen depletions frequently to 6-4 mg L^{-1} and periodically to < 2 mg L^{-1}, with chlorophyll levels averaging 7 ug L^{-1} with periodic blooms in the 10-15 ug L^{-1} range. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, the eelgrass with epiphytes and significantly impaired eelgrass habitat in the north basins is to be expected.

The elevated nitrogen levels within the Farm Pond Estuary indicate a moderate level of watershed nitrogen loading relative to the present restricted tidal flushing rates, which nearly doubles the nitrogen levels in the incoming tidal waters (see Section VI). As eelgrass within Farm Pond is a critical habitat structuring the entire system, which is presently impaired, restoration of the eelgrass resource is the primary target for overall restoration of the Farm Pond Embayment System. Restoration planning for this habitat should focus on reducing the level of nitrogen enrichment in basin waters through watershed nitrogen management and increases in tidal exchange. Note that restoration of this eelgrass habitat will necessarily result in restoration of other resources throughout the system.

Based upon the above analysis, eelgrass habitat was selected as the primary nitrogen management goal for the Farm Pond basin, with parallel restoration of infaunal habitat occurring as management alternatives are implemented for eelgrass. These goals are the focus of the MEP management alternatives analysis presented in Chapter IX.

Water Quality: The tidal waters of the Farm Pond Embayment System are currently listed under this Classification as SA. The Farm Pond Estuary is not presently meeting the water quality standards for SA waters. The result is that as required by the Clean Water Act, TMDL processes and management actions must be developed and implemented for the restoration of resources within this estuary.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels within Farm Pond indicate moderate levels of nutrient enrichment and impaired habitat quality. The oxygen data are consistent with high organic matter loads from phytoplankton production (chlorophyll-*a* levels) indicative of the observed level of nitrogen enrichment (0.52-0.53 mg N L^{-1} summer average monitoring data; 0.51 mg N L^{-1} tidally averaged level in south basin) and eutrophication of this estuarine basin. The large daily excursions in oxygen concentration also indicate significant organic matter enrichment.

Generally, the dissolved oxygen records indicate moderate depletions during the critical summer period, but with periodic significant depletions, hypoxia (<4 mg L^{-1}), of bottom waters. Oxygen records indicate that the basin of Farm Pond frequently has oxygen levels in the 4-6 mg L^{-1} range, and infrequently to the highly stressful <2 mg L^{-1} levels. These observed levels of oxygen depletion are consistent with the moderate chlorophyll levels coupled to the tidally restricted nature of the system and the very warm waters (average 24 C, maximum 28 C) which stimulate the rates of oxygen uptake in the water column and sediments.

Overall, the pattern of high nitrogen, resulting in moderate levels of phytoplankton biomass with periodic blooms and periodic low oxygen depletion was found throughout this system. The near absence of eelgrass within the northern basin and density and epiphyte growth on eelgrass in the south basin are consistent with the observed water quality conditions. Similarly, the virtual loss of infaunal habitat within the north basin and dominance of organic enrichment indicator species in the south basin also reflect nitrogen enrichment. Management of nitrogen levels through reductions in watershed nitrogen inputs and increased tidal flushing are required for restoration of eelgrass and infaunal habitats within the Farm Pond Embayment System.

Infaunal Communities: In all areas and particularly those that do not support eelgrass beds, benthic animal indicators are 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 survey of infauna communities throughout Farm Pond indicated a system presently supporting impaired benthic infaunal habitat. Infaunal habitat within the northern basin is severely degraded, based upon the very low numbers of animals present (~20 per sample) and few species (5 per sample). The southern basin, while supporting a higher habitat quality, is still significantly impaired. The designation of significant impairment stems from the presence of higher numbers of individuals and species, but a community dominated by stress tolerant species indicative of high levels of organic enrichment. About 50% of the total community consisted of a single species, *Capitella capitata*, generally found in embayments with high organic matter deposition and poor habitat quality. Diversity and Evenness were also low, averaging <2 and ~0.6, respectively (in samples with more than 75 individuals). In contrast, high quality infaunal habitat supports much higher numbers of individuals and species with high Diversity and Evenness. For example, the outer stations within Lewis Bay currently support high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), Diversity (3.69) and Evenness (0.74). Further the community is composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms found in significantly impaired basins (like Farm Pond).

There is a general increase in habitat impairment moving from south to north within Farm Pond. This trend is seen both in eelgrass and infaunal habitat quality. The observed infaunal communities are consistent with the frequent summertime hypoxia in bottom waters and the organic rich soft sediments with only a thin oxidized surface layer. The tidally averaged nitrogen levels in Farm Pond waters (0.48-0.51 mg N L^{-1}) presently are at the typical upper threshold for high quality benthic habitat, and the observed degree of impairment is generally seen at higher nitrogen levels. However, the evidence of impairment is clear and shows little variation within sites. It is likely that the habitat is more sensitive to nitrogen enrichment due to its reduced tidal exchange and depositional nature. Classification of habitat quality necessarily included the structure of the estuarine basin, specifically that it is fully representative of a tidal embayment, as opposed to a tidal river or salt marsh basin. Based upon this analysis it is clear that the embayment basins are presently supporting significantly impaired to severely degraded benthic habitat whose proximate cause is organic matter enrichment and hypoxia and whose ultimate cause in nitrogen enrichment. Since Farm Pond does not exhibit strong horizontal gradients in water quality parameters and since the system presently has impaired eelgrass habitat, lowering the nitrogen to improve eelgrass habitat, primarily in the southern basin, will also be sufficient to restore infaunal animal habitat so no separate nitrogen threshold for infauna is required for this system.

It should be noted that the observed pattern of shellfish growing area determined by Massachusetts DMF is consistent with the observed organic rich sediments within the basins and the hypoxia in the bottom waters, the "ring" encompasses the shallows where hypoxia is less frequent and severe. Improving benthic animal habitat quality should also expand the shellfish growing area within this system.

Table VIII-1. Summary of nutrient related habitat quality within the Farm Pond Estuary within the Town of Oak Bluffs, MA, based upon assessments in Section VII. The single main basin of this tidally restricted embayment consists of basins to the north and south of Woody Island.

Health Indicator	Farm Pond Embayment System	
	South Basin	**North Basin**
Dissolved Oxygen	MI/SI[1]	MI/SI[1]
Chlorophyll	H/MI[2]	H/MI[2]
Macroalgae	MI[3]	MI[3]
Eelgrass	H/MI[4]	SI[5,6]
Infaunal Animals	SI[7]	SD[8]
Overall:	**MI[9]**	**SI[10]**

1 – oxygen depletion frequently 6 mg/L to 4 mg/L, infrequently to <2 mg/L;
2 – moderate summer chlorophyll levels generally <10 ug/L, averaging 7.5 ug/L, average level in summer water quality monitoring samples (2003-2007, 2009) was 6.7 ug/L.
3 -- patches of drift algae, *Cladophora* and *Ulva*.
4 – eelgrass bed primarily healthy and stable, with beds near flux station FRM-4 with epiphytes
5 – eelgrass bed heavy with epiphytes and very sparse and patchy with low coverage.
6 -- MassDEP (C. Costello) indicates that eelgrass lost from this system between 1951-1995.
7 -- moderate numbers of individuals, low number of species, diversity & Evenness, dominated by organic enrichment and stress tolerant opportunistic species, (*Capitella* accounting for 50% of total organisms)..
8 -- low numbers of individuals, species, diversity & Evenness to the extent that almost no organisms are found, ~20 organisms per sample, mainly stress tolerant organisms.
9 -- Moderate Impairment, primarily due to periodic D.O. depletion and significantly impaired animal communities, but with an apparently stable eelgrass community, moderate summer chlorophyll levels and low-moderate accumulation of drift macroalgae.
10 -- Significant Impairment , primarily due to periodic D.O. depletion and significantly degraded animal communities and only sparse eelgrass with epiphytes, but moderate summer chlorophyll levels and low-moderate accumulation of drift macroalgae.

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

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates that will support acceptable habitat quality throughout an embayment system is to first identify a sentinel location within the embayment and secondly, to determine the nitrogen concentration within the water column that will restore the location to the desired habitat quality. The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined (Section VIII.2), the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved (Section VIII.3).

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

The Farm Pond Embayment System presently supports nitrogen related habitat impairment throughout the tidal reach. While there is little horizontal gradient in water quality parameters within Farm Pond due to horizontal mixing, there is a clear gradient of declining habitat quality moving from south to north. The north basin is significantly impaired basin relative to eelgrass, as it has only sparse patchy eelgrass coverage. In contrast, the relatively dense eelgrass beds in the southern basin, which appear to be declining only slightly, are moderately impaired. The moderate impairment designation stems from the apparent reduction in coverage and the observed moderate density of epiphytes on the eelgrass blades (Section VII-2). Similarly, the basins have impaired infauna habitat, with severely degraded habitat in the northern basin, which is virtually devoid of animals, and significantly degraded habitat in the southern basin which has moderate numbers of animals, but is dominated (50%) by the organic enrichment tolerant species, *Capitella capitata* (Section VII-3). These levels of impairment are also reflected in the observed periodic hypoxia, phytoplankton blooms and nitrogen enrichment (Table VIII-1).

The eelgrass and water quality information supports the conclusion that eelgrass beds within the entire main basin should be the primary target for restoration of the Farm Pond Embayment System and that restoration requires a reduction in nitrogen enrichment through appropriate watershed nitrogen management and/or increased tidal exchange. From the eelgrass surveys of 1997 and 2006 it appears that eelgrass coverage could increase by ~30% over the present bed area, with parallel restoration of the significantly impaired and degraded benthic animal habitat. As the south basin has slightly higher TN levels than other regions of Farm Pond, the sentinel station for the Farm Pond Estuary is the southern most long-term water quality monitoring station (FRM-3, Chapter VI). Presently, the sentinel station has a tidally averaged TN of 0.51 mg L-1, consistent with the observed epiphyte growth on the eelgrass and apparent decline in coverage. It should be noted that: 1) given that eelgrass is essential to the overall structure and productivity of Farm Pond's estuarine resources, 2) improving this habitat will result in parallel restoration of other habitats and 3) water quality impairments will be rectified, restoration of eelgrass habitat was determined to be the primary target for restoration of the overall Farm Pond System.

Total nitrogen levels (TN) within Farm Pond, with its moderately stressed but relatively stable eelgrass beds, presently show summer-time tidally averaged levels of 0.48 - 0.51 mg N L^{-1}), as determined from the validated water quality model (Chapter VI). Farm Pond is a shallow water basin with depths generally less than 1 meter. In shallow systems like Farm Pond, eelgrass beds are sustainable at higher TN (higher chlorophyll-*a*) levels than in deeper waters, because of the "thinner" water column that light has to pass through to support eelgrass growth (less water to penetrate). In systems analogous to Farm Pond, for example at similar depths in Bournes Pond, eelgrass can be still be found (although heavy with epiphytes) at the mouth of the upper tributary at a tidally averaged TN concentration of 0.481 mg TN L^{-1}, while the more stable beds in the lower region of Israel's Cove have at a tidally averaged TN of 0.429 mg TN L^{-}

[1]. Similarly, areas non-supportive of healthy beds also have higher TN levels, eelgrass within Hamblin Pond persisted at a TN level of 0.5 mg L-1, but diminished to a few small patches.

The levels of TN and quality of the eelgrass habitat observed in Farm Pond are comparable to similar shallow systems in the region, where at these TN levels the eelgrass is stressed, has epiphytes and is just beyond its tolerance limit. Based upon the information above and in Chapter VII, the depth of Farm Pond and its moderate level of eelgrass impairment and TN levels of 0.48 - 0.51 mg L^{-1}, it appears that the system is presently slightly beyond its nitrogen threshold for sustainable eelgrass coverage. This assessment is based upon the fact that eelgrass presently colonizes much of the main basin and that epiphyte growth is moderate and there has been little recent loss of bed coverage.

The TN levels and eelgrass habitat quality in Farm Pond are most similar to that in Bournes Pond at TN levels of 0.481 mg L^{-1}, and consistent with the observed eelgrass decline in Hamblin Pond at 0.5 mg L^{-1}. In both of these systems, the eelgrass habitat was just over the threshold for eelgrass habitat impairment in those basins. Therefore to restore eelgrass habitat in Farm Pond the nitrogen concentration (tidally averaged TN) at the sentinel location within the southern basin needs to be lowered to 0.45 mg TN L^{-1}. This threshold levels is consistent with high quality shallow water habitat in Bournes Pond and is similar to the condition of eelgrass within the Parker's River system, tidally averaged TN level (0.45 mg TN L^{-1}). The TN threshold for Farm Pond represents a relatively high threshold as a result of the shallow depth of the entirety of the potential eelgrass habitat. The goal, to achieve the nitrogen target at the sentinel location and restore quality eelgrass habitat within Farm Pond, will also result in the restoration of infaunal habitat throughout the System. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations are discussed in Section VIII.3, below.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Farm Pond system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharge only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for Farm Pond. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment in cases where such features exist. 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 required nearly 40% removal of septic load (associated with direct groundwater discharge to the embayment) for the entire system. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. For example, removal of 39% of the septic load from the Farm Pond watershed results in a 26% reduction in total watershed nitrogen load. 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 Nantucket 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-4. To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN concentrations of typically greater than 25% over background is required in the system, between the main harbor basin and the marsh.

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

The basis for the watershed nitrogen removal strategy utilized to achieve the embayment thresholds may have merit, since this example nitrogen remediation effort is focused on watersheds where groundwater is flowing directly into the estuary. For Farm pond, future nitrogen management could take advantage of improvements to tidal flushing by constructing a wider inlet to ensure the most cost-effective nitrogen reduction strategies. The establishment of a larger tide range in the pond would increase tidal flushing, and help to reduce N concentrations throughout the system, and reduce the amount of watershed N load reduction necessary to achieve the target threshold concentrations. A culvert widening scenario is discussed in Chapter IX.

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

sub-embayment	present septic load (kg/day)	threshold septic load (kg/day)	threshold septic load % change
Farm Pond System Total	4.060	2.484	-38.8%

Table VIII-3. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer, and WWTF loads) used for modeling of present and threshold loading scenarios of the Farm Pond system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Farm Pond System Total	5.970	4.394	-26.4%

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Farm Pond System Total	4.394	0.490	-0.751

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change over background in Nantucket Sound (0.294 mg/L), for the Farm Pond system. The threshold stations are shown in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
North Basin	FAM-1	0.496	0.444	-25.5%
Mid Pond	FAM-2	0.480	0.433	-25.7%
South Basin	**FAM-3**	**0.508**	**0.453**	-26.0%

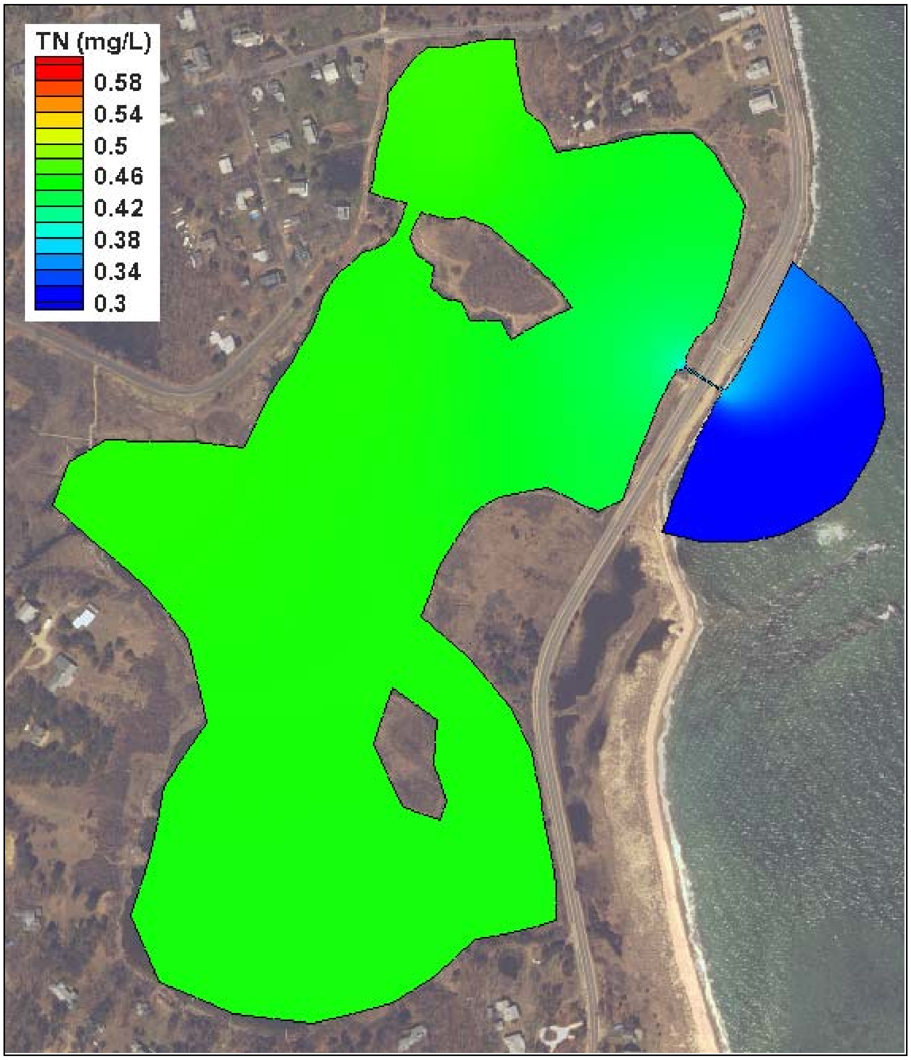


Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Farm Pond estuary, for threshold conditions.

IX. HYDRODYNAMIC AND WATER QUALITY MODEL SCENARIOS

After determining the flushing characteristics of the existing Farm Pond system, a further analysis was performed to investigate possible modifications to the inlet with the purpose of identifying the likely optimum inlet configuration with regards to tidal exchange and inlet maintenance. The first two sections of this chapter detail the analysis that was performed for MCZM in 2006 (Kelley, 2006). Additional TN modeling results are presented in this chapter for the optimum inlet cross section.

IX.1 TIDAL CHARACTERISTICS OF INLET SCENARIOS

Using the calibrated hydrodynamic model of Farm Pond, four inlet scenarios were modeled to evaluate how different inlet widths would impact the tidal characteristics of the Pond. Each modeled scenario was run with the inlet in its present location under Beach Road. From the perspective of tidal flushing, the exact location of the inlet culvert under the road is not important, as long as the culvert opens directly to Nantucket Sound, and has roughly the same length.

In addition to the present 4 foot culvert, the four modeled inlet scenarios were 8, 12, 16 and 24 foot wide box culverts. For each case, the finite element mesh from the calibrated model representing present conditions was modified to include the new inlet and re-run using the tidal open boundary conditions corresponding to the model calibration time period. In this manner, changes to tidal dynamics resulting from the inlet alternatives can be quantitatively assessed and compared directly with present conditions.

A comparison of model results is presented in Figure 1 and Table 1 show how velocities vary with the different modeled scenarios. Velocities between 2 and 3 feet per second (ft/sec) are considered optimal for tidal inlets, since velocities in this range help to keep the inlet channel clear of sediment. Velocities greater than this range indicate that the inlet is likely undersized and overly restrictive to tidal flow. Alternately, velocities less than this range indicate an oversized inlet that is likely unstable and will equilibrate to a smaller cross-sectional area.

The results in Figure 1 and Table 1 show that the present inlet is undersized, when evaluated based on optimum velocities in the inlet channel. With average tidal velocities equal to or greater than 4.8 ft/sec, it is apparent that the inlet culvert is severely restricting tidal exchange between the Pond and Nantucket Sound. Considering inlet velocities only, the most favorable scenarios are the 12, 16 and 24 foot inlets. For these three inlet alternatives, mean tidal velocities are most favorable for maintaining the inlet opening.

A further comparison of tidal characteristics for the different modeled inlet options is presented in Table 2. These results show that as the tide range increases as the inlet width is increases, there are corresponding increases in the elevation of mean high water (MHW), though for even the 24 foot inlet the increase in MHW is only 0.4 ft. The ratio of Pond versus Sound tide range emphasizes that even though the tide ranges for each of the modeled alternatives is generally around one foot, the tide range in the Pond is limited obviously by the offshore tide range. Hence, though the tide range for the 16 foot inlet is only 1.1 foot, it is nearly 50% of the offshore tide range. This is a great improvement over present conditions, where the Pond tide range is less than 20% of the offshore range.

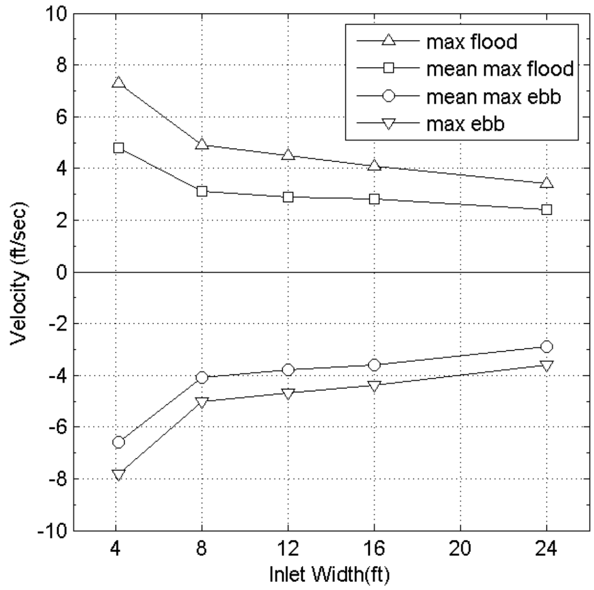


Figure IX-1. Plot of maximum and mean depth-averaged flood and ebb tide velocities as a function of inlet width, for five modeled culvert scenarios.

Table IX-1. Comparison of modeled max and mean flood and ebb tide velocities for modeled inlet options for Farm Pond.

Inlet Width (ft)	4.1	8.0	12.0	16.0	24.0
Max Flood Velocity (ft/sec)	7.3	4.9	4.5	4.1	3.4
Mean Flood Velocity (ft/sec)	4.8	3.1	2.9	2.8	2.4
Mean Ebb Velocity (ft/sec)	-6.6	-4.1	-3.8	-3.6	-2.9
Max Ebb Velocity (ft/sec)	-7.8	-5.0	-4.7	-4.4	-3.6

Table IX-2. Comparison of tidal characteristics of modeled inlet options for Farm Pond.

Inlet Width (ft)	4.1	8.0	12.0	16.0	24.0
Pond Mean Tide Range (ft)	0.4	0.6	0.9	1.1	1.4
Pond vs. Offshore Tide Range Ratio	0.19	0.27	0.39	0.48	0.58
Mean Higher High Water (ft, MLW)	2.3	2.4	2.5	2.6	2.7

Residence (flushing) times were calculated for each inlet scenario (Table 3). The results in this table show that changes to the average tidal prism of the Pond are equivalent to the changes seen in the tide range. For example, for the 16 foot-wide inlet the tide range increases by 150% of the present range, which is the same percentage increase for the average tide prism. Computed residence times are affected differently. Inlet widths greater than 16 feet have greatly diminishing benefits with regards to computed flushing times. The 24 foot inlet is only 7% more efficient at flushing than the 16 foot inlet from the comparison of residence times. The 16 foot inlet improves the Pond flushing time by 61% compared to present conditions.

Table IX-3. Comparison of flushing characteristics of modeled inlet options for Farm Pond.					
Inlet Width (ft)	4.1	8.0	12.0	16.0	24.0
Mean Volume (ft^3)	5,167,000	5,089,000	5,059,000	5,029,000	4,976,000
Mean Prism (ft^3)	738,000	1,039,000	1,479,000	1,843,000	2,217,000
System Flushing Time (days)	3.62	2.53	1.77	1.41	1.17

IX.2 PARTICLE TRACKING MODEL RESULTS OF SELECTED SCENARIOS

To further investigate the flushing performance of the pond as the inlet is widened, two of the options and present conditions were selected for the particle tracking model analysis. For this analysis, the RMATRK particle tracking model (DeGeorge, 1996) was used to simulate the fate of particles released into Farm Pond. The RMATRK model transports discrete objects through a water body and operates as part of the RMA suite of models that the RMA2 hydrodynamic model is a part. The inputs to RMATRK include the RMA model grid, the hydrodynamic output from RMA-2, and the initial positions and release times of the particles to be tracked. The output of the model is simply the positions of all the particles at each requested time step. For the simulations executed for this analysis, the RMATRK model time step was the same as that used for the hydrodynamic model and tide data (i.e., 10 minutes).

The inlet scenarios selected for the particle tracking analysis were present conditions, and the 8 and 16 ft-wide inlets. The 16 foot inlet was selected as one of the particle tracking model because the hydrodynamic analysis showed that the flushing improvements were optimal for this width. The 8 foot inlet was modeled to provide a reference point to show how the system behavior varies between present conditions and the 16 foot option. For each scenario, 283 particles were released at the same time in the model domain. The particles were spatially distributed by grid element; one particle was placed in each element of the main basin of the pond, excluding elements on the marsh plain. The model was then run for a simulated 300 hours (12.5 days) after the release time.

Particle tracking model results are presented in Figure IX-2 and Table IX-4 for the three modeled scenarios. The particle half-life level (142 particles) is drawn on the plot of Figure IX-2. This line indicates the point where half of the original particles remain in the model domain, the rest having been flushed out beyond the model grid.

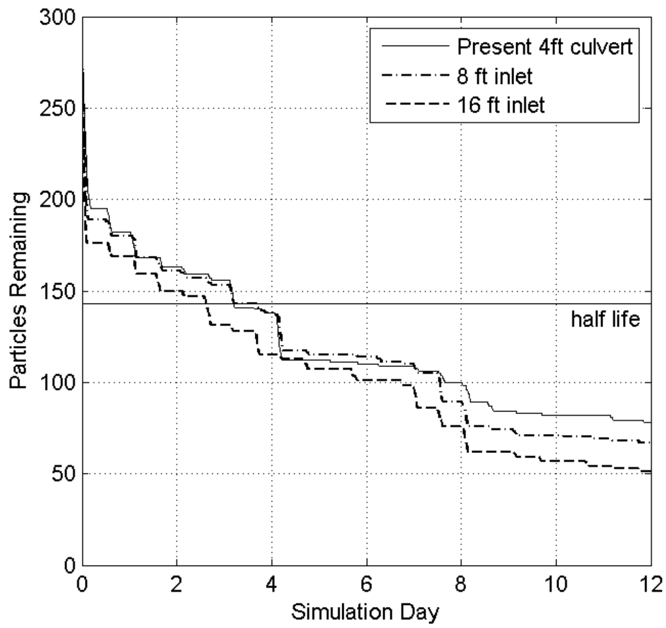


Figure IX-2. Plot of particle fate as a function of time for three modeled inlet scenarios, including present conditions, and both 8 ft and 16 ft inlets.

Table IX-4. Comparison of particle half-lives computed for modeled culvert options for Farm Pond using the RMATRK particle tracking model.

Inlet Width (ft)	4.1	8.0	16.0
Particle Half-Life (days)	3.21	3.20	2.63

Results presented in Table IX-4 show that the present 4 foot culvert and the modeled 8 foot option have nearly the same particle half-life of 3.2 days. The 16 foot option shows an improvement over the 8 foot inlet, with a particle half-life of 2.63 days. The computed particle half-lives are conceptually similar to the residence times computed based on the tide prism and mean system volume (Table IX-3), but the particle tracking results show a different trend than the residence times computed using the tidal prism method. The main cause of this difference is due to the underlying assumption of the tidal prism method, which is that waters in the basin are well mixed at all times. Because of this assumption, the half-life computed using the particle tracking model results is more representative of the actual system. The particle model does not require that the modeled particles be evenly distributed, and allows higher concentrations of particles in areas of the modeled domain.

Therefore, an embayment that would seem to flush well using the tide prism method may be shown to flush less well by the particle tracking model if particles tend to collect and remain in areas of an embayment system rather than eventually exiting the system through the inlet. This can be seen in the particle model results presented in Figure IX-3. For present conditions (Figure IX-3.b), the model results show that after 300 simulated hours, particles have a tendency to collect in the southern portion of the system (below 2,624,500 N) and also in the western cove of Farm Pond (around 2,625,000 N). The results from the 8 and 16 foot scenario runs show an improvement in particle distribution over present conditions, with the best results from the 16 foot inlet model. At the end of the 300 hour simulation, the 16 foot inlet has approximately 33% fewer particles remaining than the model run of present conditions. By comparison, the 8 foot inlet has only 17% fewer particles than present conditions.

Results of the particle tracking model indicate that more stagnant areas exist along the western and southern edges of the pond. Relocation of the culvert to another area of State Road (e.g. within 300 feet of its existing location) would have little influence on overall pond circulation patterns. Therefore, there appears to be no benefit to changing the location of the existing culvert.

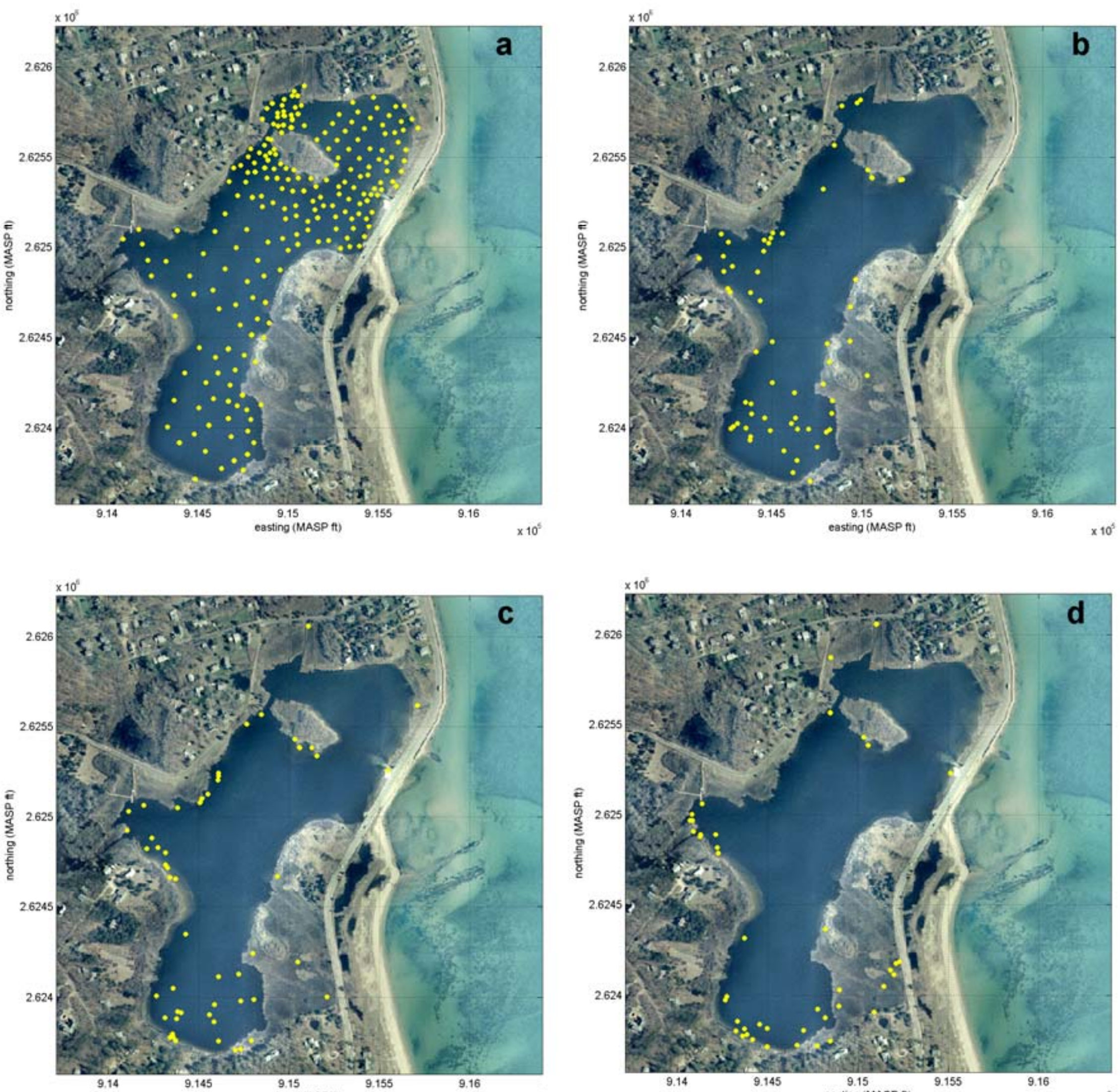


Figure IX-3. Particle tracking model results, showing initial conditions (a), and three modeled inlet scenarios at 300 hours (12.5 days) after initial particle release. Modeled scenarios are: (b) present conditions with a 4 ft culvert, (c) an 8 ft wide box culvert, and (d) a 16 ft wide box culvert.

IX.3 WATER QUALITY MODEL RESULTS OF SELECTED OPTIMAL INLET

The hydrodynamic analysis of present conditions show that the existing culvert is undersized, when evaluated based on optimum velocities in the inlet channel. Considering inlet velocities only, the most favorable modeled inlet scenarios were those with inlet channel widths greater than 12 feet. For these modeled scenarios, mean tidal velocities were most favorable for maintaining the inlet opening. The results of the particle tracking model runs show that the greatest improvement in particle distribution over present conditions occurs with the 16 foot-wide inlet scenario.

Since the 16 foot option provides the best flushing improvements with the narrowest channel width, this alternative was selected as a run using the RMA-4 water quality model. By modeling TN, the effect of the wider inlet can be determined quantitatively, and compared directly to existing conditions. The TN model of the pond with 16 foot culvert was set up to include the same N loadings used for present conditions (Table VI-2). The N loading for this culvert scenario relies on the assumption that N flux from bottom sediments will remain the same with the new inlet.

Results of the 16 foot culvert TN model are presented in Table IX-5, where the comparison to the model of present conditions is also shown. Generally, TN concentration reductions greater than 66% occur across the entire pond. The TN concentration at the threshold station is well below the target of 0.45 mg/L set for the pond in Chapter VIII. This indicates that restoration of the pond is likely by increasing the size, without any change to the watershed N load (i.e., no sewering required). Therefore, inlet improvements offer a very cost effective alternative to sewering, since the target N concentration can be achieved by a wider inlet.

Table IX-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change over background in Nantucket Sound (0.294 mg/L), for the Farm Pond system. The threshold stations are shown in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
North Basin	FAM-1	0.496	0.364	-65.5%
Mid Pond	FAM-2	0.480	0.347	-71.7%
South Basin	**FAM-3**	**0.508**	**0.368**	**-65.5%**

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