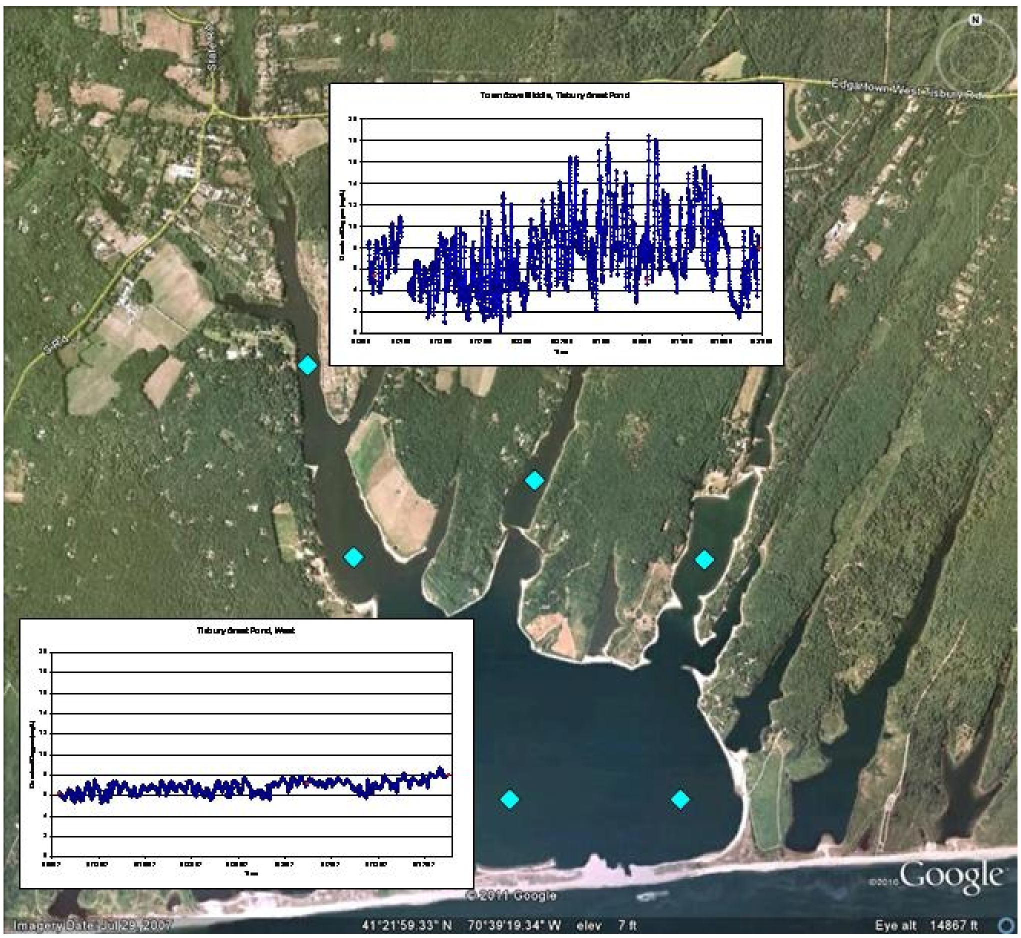
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Tisbury Great Pond / Black Point Pond System Towns of Chilmark and West Tisbury, MA



University of Massachusetts Dartmouth
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Massachusetts Department of
Environmental Protection

FINAL REPORT – May 2013

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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 Tisbury Great Pond embayment system, a coastal embayment primarily within the Towns of Chilmark and West Tisbury, Massachusetts. Analyses of the Tisbury Great Pond embayment system was performed to assist the Towns of Chilmark and West Tisbury with up-coming nitrogen management decisions associated with the current and future wastewater planning efforts of the Towns, as well as wetland restoration, management of anadromous fish runs and shell fisheries as well as the development of 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 Towns of Chilmark and West Tisbury 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 Tisbury Great Pond embayment, (2) identification of all nitrogen sources (and respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Towns) for the restoration of the Tisbury Great 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 Tisbury Great Pond embayment system within the Towns of Chilmark and West Tisbury 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 Towns of Chilmark and West Tisbury have recognized the severity of the problem of eutrophication and the need for watershed nutrient management and are currently engaged in wastewater management at a variety of levels. Moreover, the Towns of Chilmark and West Tisbury are beginning to recognize the need to work collaboratively regarding the future implementation of the MEP nutrient threshold analysis of the Tisbury Great Pond system. For the Town of Chilmark, this analysis of the Tisbury Great Pond system will be considered relative to the soon to be completed nutrient threshold analysis of Chilmark Pond and Menemsha/Squibnocket Pond system to plan out and implement a unified town-wide approach to nutrient management for Chilmark. The Towns of Chilmark and West Tisbury with associated working groups (e.g. Chilmark Pond Association, Tisbury Great Pond Riparian Association, Martha's Vineyard Shellfish Group) 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 Tisbury Great Pond embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted primarily by the Martha's Vineyard Commission and with field support from the Towns of Chilmark and West Tisbury. The water quality monitoring program was conducted with technical guidance from the Coastal Systems Program at SMAST (see Section II). Evaluation of upland nitrogen loading was conducted by the MEP and data was provided by the Planning Departments in the Towns of Chilmark and West Tisbury as well as the Martha's Vineyard Commission. The watersheds utilized in the MEP assessment are largely based on delineations created and used by the Martha's Vineyard Commission (MVC). The portions of the watershed within the outwash plain have been delineated based on regional groundwater contours (Delaney, 1980) and with more refined water level readings in selected areas (Wilcox, 1996). In 1994, Whitman and Howard produced a groundwater model with a domain that covered Martha's Vineyard eastern moraine and the outwash plain; this model was based on the publicly available USGS MODFLOW three-dimensional, finite difference groundwater model code. The Wilcox (1996) watershed delineation completed for the MVC utilizes all of the previous characterizations. These watershed delineations and the land-use data was used to determine watershed nitrogen loads within the Tisbury Great Pond embayment system and each of the systems sub-embayments as appropriate (current and build-out loads are summarized in Section 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 Tisbury Great 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 Atlantic Ocean source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Tisbury Great 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 Tisbury Great 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, in concert with modifications to the pond opening schedule until the nitrogen levels reached the threshold level at the sentinel stations chosen for the Tisbury Great Pond system. It is important to note that load reductions can be produced by reduction of any or all sources, increasing flushing of the system with clean open ocean water 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 Tisbury Great Pond embayment system in the Towns of Chilmark and West Tisbury. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. Hydrodynamic and water quality model runs were performed to investigate quantitatively how flushing and TN concentrations would change in the Tisbury Great Pond system if an additional August opening could be achieved.

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 40% of the controllable watershed load to the Tisbury Great Pond embayment system and are more manageable than other of the nitrogen sources (e.g. agriculture @ 44% of the controllable load), the ability to achieve needed reductions through this source is a good gauge of the feasibility for restoration of this system.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Tisbury Great 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 Tisbury Great Pond Estuary is showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Section VII), indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

The Tisbury Great Pond Embayment System is comprised of three major functional units, each with different levels of habitat quality. The main basin of Tisbury Great Pond (e.g. the lagoon formed by the barrier beach) is moderately to significantly impaired due to its complete loss of historic eelgrass coverage and has generally moderate impairment of its benthic animal habitat. The small tributary coves (Town Cove, Tiah Cove, Pear Tree Cove and Deep Bottom/Thumb Cove) are shallow narrow "finger basins" to the main basin and all have moderate-significant impairment of benthic animal habitat and no historic eelgrass coverage. They are structurally and functionally similar and are the major initial receptors of watershed nitrogen inputs. The third unit, Black Point Pond, differs from the others as it functions as a shallow pond surrounded by wetlands (>40 acres), which likely persist due to the topography and relatively isolated hydraulic characteristics of the pond (restricted exchange through Crab Creek to the main basin). As a wetland influenced salt pond, Black Point Pond supports relatively high quality benthic animal habitat and has no evidence of supporting (historic or present) eelgrass habitat.

Overall, Tisbury Great Pond and its tributary coves, exclusive of Black Point Pond, are presently showing a moderate to high level of habitat impairment (eelgrass and infaunal animals) resulting from summer oxygen depletion and organic enrichment primarily from phytoplankton production, parameters directly affected by nitrogen enrichment. The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a levels indicate moderately nutrient enriched waters and impaired habitat quality within the upper and lower basins. The oxygen data is consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-a. The periodic elevated oxygen levels observed in some of the Coves provides additional evidence that this system is presently receiving nitrogen inputs above the threshold required to maintain high quality estuarine habitat at its present rate of tidal exchange. The oxygen records show that the inner sub-embayments of Tisbury Great Pond, specifically Town Cove and Tiah Cove, which receive significant watershed nitrogen loads relative to their volumes and turnover rates, have the largest daily oxygen excursions, a nutrient related response. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The central region of Town Cove has clear evidence of oxygen levels above atmospheric equilibration providing additional documentation of potential impairment through nitrogen over-enrichment.

At present, eelgrass beds are not present in the Tisbury Great Pond Embayment System, although observations suggest that very small patches of eelgrass in the lower portion of the main basin near the barrier beach may occur after periods when the pond is open to tidal exchange for extended periods and anecdotal evidence supports the historical presence of eelgrass habitat under higher water quality conditions. The current lack of eelgrass beds are consistent with the elevated chlorophyll-*a* and low dissolved oxygen levels and watercolumn nitrogen concentrations within this system. That the historic eelgrass beds were restricted to the shallow margins versus within the "deeper" regions of the lower basin (1951) also indicates that nitrogen enrichment plays the key role in the distribution of eelgrass historically in this system and the absence of eelgrass at present.

Over the past several decades, eelgrass has generally not existed within the Tisbury Great Pond Embayment System. At the present moderate levels of watershed nitrogen loading with only periodic tidal exchange, the level of nitrogen enrichment has resulted in conditions no longer supportive of eelgrass (high chlorophyll, oxygen depletion, high turbidity). In addition, much of the system has structural impediments to supporting eelgrass even at moderate levels of nitrogen enrichment. The central region of the main basin and much of Deep Bottom and Town Coves are relatively deep requiring clearer waters (light penetration) than many shallow tidal estuaries within the region. The loss of eelgrass beds within the main basin of Tisbury Great Pond relative to historical distribution (1951 photo interpretation and anecdotally supported) is expected given the measured levels of nitrogen enrichment and resulting chlorophyll-*a* and dissolved oxygen. Total nitrogen levels (TN) within the lower basin have mean summer time levels of 0.51 - 0.53 mg N L^{-1} compared to the levels in other similarly configured southeastern Massachusetts estuarine basins currently supporting eelgrass, 0.35-0.45 mg N L^{-1} (range of Cape Cod systems).

Other key water quality indicators pertinent to eelgrass viability, dissolved oxygen and chlorophyll-*a*, show similar levels of moderate enrichment with periodic oxygen depletions below 5 mg/L and chlorophyll levels in blooms reaching 10-20 ug/l. While there is only a small gradient in nutrient related water quality parameters within this embayment system, the coves do generally support higher TN levels and larger phytoplankton blooms (chlorophyll-*a* averaging 15-20 ug L^{-1}, blooms 30-40 ug L^{-1}) and greater oxygen depletion. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, the lack of eelgrass habitat within the tributary Coves and the loss of eelgrass habitat within the main basin of Tisbury Great Pond is consistent with observed eelgrass habitat and areas of loss in numerous other estuaries throughout the region. Management of nitrogen levels through reductions in watershed nitrogen inputs and increased tidal flushing, as appropriate, are required for restoration of eelgrass and infaunal habitats within the Tisbury Great Pond Embayment System.

Overall, the infauna survey indicated that most sub-basins comprising the Tisbury Great Pond Embayment System are presently beyond their ability to tolerate additional nitrogen inputs without impairment. The exception is Black Point Pond which is functionally a wetland basin (e.g. a pond surrounded by significant wetland area). There was a clear spatial pattern in habitat quality, with moderately to significantly impaired benthic animal habitat found in the upper tributary coves and moderately impaired areas within the large main basin (and as noted, Black Point Pond). The Benthic Survey did not reveal any areas of severe degradation, as indicated by low numbers of individuals and species or dominance by opportunistic stress indicator species (such as Capitellids and Tubificids). In fact, at all locations throughout the sub-basins of this embayment system, there were high numbers of individual (>600 per grab sample), moderate to high numbers of species (14 to 20 per sample) and low numbers of Capitellids and Tubificids (generally <10% of community). Species numbers of 20-25 generally indicate high quality benthic habitats. While there is little evidence of severe nitrogen related impairment of benthic animal communities, most areas clearly showed evidence of moderate impairment associated with nitrogen and organic matter enrichment.

The upper tributary sub-basins, specifically Town Cove, Pear Tree Cove, Tiah Cove are all showing moderate-high levels of impairment related to their elevated chlorophyll-a levels and periodic oxygen depletions to levels stressful to estuarine animals living within the sediments. Similarly, Deep Bottom/Thumb Cove and the main basin of the great pond are generally showing a moderate level of impaired benthic habitat. While the species numbers and numbers of individuals remain high throughout the system, the community diversity and evenness within each of the more impaired coves is low and indicative of a community under ecological stress.

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 Tisbury Great Pond system in the Towns of Chilmark and West Tisbury were comprised primarily of wastewater nitrogen and agricultural sources. Land-use and wastewater analysis found that generally about 40% of the controllable watershed nitrogen load to the embayment was from wastewater and 44% from agricultural activity.

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 Farm Pond, 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 Tisbury Great Pond.

The threshold nitrogen levels for the Tisbury Great Pond embayment system in Chilmark and West Tisbury were determined as follows:

Tisbury Great Pond Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Tisbury Great Pond system should reflect both recent pre-degradation habitat quality and be reasonably achievable. Based upon the assessment data (Section VII), the Tisbury Great Pond system is presently supportive of habitat in varying states of impairment, depending on the component sub-basins of the overall system (e.g. tributary basins in the upper portions of the system which receive majority of fresh surfacewater inflow compared to shallower fringing areas in the lower portion of the main basin).

- The primary habitat issue within the Tisbury Great Pond Embayment System relates to the general loss of eelgrass beds and impaired infaunal habitat. Integrating all of the available eelgrass data, it appears that there has been significant loss of eelgrass coverage within Tisbury Great Pond, namely along the southeastern margin of the lower main basin. The loss is on the order of 50 acres, but the density cannot be fully quantified. This eelgrass loss indicates that this basin is presently supporting significantly impaired eelgrass habitat and that restoration of this habitat should necessarily be part of nitrogen related restoration of the Tisbury Great Pond System. Note that restoration of this eelgrass habitat will necessarily result in restoration of other resources, such as infaunal animal habitats, throughout the Tisbury Great Pond Embayment System. Also, nitrogen management for eelgrass restoration will protect Black Point Pond from nitrogen over-enrichment, either directly through management of nitrogen sources within the Black Point Pond watershed or through lower nitrogen concentrations in the adjacent main basin waters..

- The integration of all information available clearly supports a nitrogen threshold for restoration of sparse eelgrass habitat within the main basin of Tisbury Great Pond of 0.46 mg N L^{-1} and a secondary target nitrogen threshold for healthy infaunal habitat within the tributary Coves of 0.48 mg N L^{-1} (time averaged). The modeling simulations in Section VIII-3 targeted the eelgrass threshold, and established that the secondary threshold for restoration of benthic animal habitat would be met within the tributary Coves. This significant lowering of average TN levels within the lower basin of Tisbury Great Pond will also simultaneously improve benthic animals throughout this embayment system. As the threshold nitrogen level is lower than present conditions watershed management should focus on keeping future build-out nitrogen loads below levels that would result in nitrogen levels at the sentinel station from exceeding the threshold.

- To restore benthic habitat, load reduction focused on lowering average TN levels of stations TGP 4, TGP 5 and TGP 6 to 0.48 mg/L during the summer months, when benthic regeneration and algae production is greatest. To restore a modest level of eelgrass habitat (consistent with the uncertainties in the historic distribution), the management scenario also focused on lowering of time-averaged TN concentrations in the lower main basin of the pond to 0.46 mg/L (at monitoring station TGP 7) over the same period. Both goals were achieved by reducing the watershed loading to the pond, together with an additional mid-summer breach. Watershed loading was reduced from present conditions until the combined time averaged TN concentration would remain below 0.48 mg/L across stations TGP 4, TGP 5 and TGP 6 and below 0.46 mg/L for station TGP 7, during a 100-day period, from the end of May to mid-September.

For restoration of the Tisbury Great 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 in appropriate areas in the lower region of the Tisbury Great Pond system (taking into consideration depth and basin structure) as well as infaunal habitat within the shallow sediments throughout the embayment inclusive of the tributary coves.

It is important to note that the analysis of future nitrogen loading to the Tisbury Great 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 Lagoon Pond estuarine system is that restoration will necessitate a reduction in the present (Chilmark 2010 and West Tisbury, 2010) 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 Tisbury Great Pond (GP) system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Surface water loads to estuarine waters of Tisbury Great Pond are presented separately from the loads of the sub-embayments to which they discharge.

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 Net Total Load[6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
TISBURY GREAT POND SYSTEM										
groundwater sources										
Deep Bottom Cove	2.803	1.570	1.233	-	2.803	1.507	0.550	4.859	0.54	0.48
Tiahs Cove	2.247	1.110	1.137	-	2.247	0.775	-1.338	1.684	0.42	0.48
Pear Tree Cove	3.836	2.137	1.699	-	3.836	0.258	0.007	4.100	0.49	-
Tisbury GP main basin	22.096	15.688	6.408	-	22.096	7.830	9.594	39.520	0.41-0.64	0.46
Black Point Pond	0.800	0.353	0.447	-	0.800	0.926	6.170	7.896	-	-
surface water sources										
Mill Brook	8.644	6.342	2.301	-	8.644	-	-	8.644	-	-
Tiasquam River	5.556	2.636	2.921	-	5.556	-	-	5.556	-	-
Tisbury GP System Total	45.981	29.836	16.145	**-**	45.98	11.296	14.982	72.259	**0.41-0.64**	**0.46-0.48**

[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. Atmospheric loads to surface water inputs are included with their respective watershed load.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 1995 – 2007 and 2011 data, ranges show the upper to lower regions (highest-lowest) of a sub-embayment.
[8] Average concentration through summer months, achieved by load reduction and successful breaching of the inlet in late spring and mid-summer.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Tisbury Great Pond (GP) system.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
TISBURY GREAT POND SYSTEM						
groundwater sources						
Deep Bottom Cove	2.803	2.803	1.507	0.550	4.859	*0.0%*
Tiahs Cove	2.247	2.247	0.775	-1.338	1.684	*0.0%*
Pear Tree Cove	3.836	3.836	0.258	0.007	4.100	*0.0%*
Tisbury GP main basin	22.096	16.969	7.830	8.901	33.700	*-23.2%*
Black Point Pond	0.800	0.800	0.926	6.170	7.896	*0.0%*
surface water sources						
Mill Brook	8.644	7.033	-	-	7.033	*-18.6%*
Tiasquam River	5.556	3.512	-	-	3.512	*-36.8%*
Tisbury GP System Total	45.98	37.199	11.296	14.289	62.784	*-19.1%*

(1) Composed of combined natural background, fertilizer, runoff, and septic system loadings.
(2) Target threshold watershed load is the load from the watershed needed to meet the embayment threshold concentrations 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 Tisbury Great 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. 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, we would like to thank the long standing efforts of the Tisbury Great Pond Riparian Association who have been steadfast champions for monitoring the state of the pond and educating the public.

Staff from the Martha's Vineyard Commission and volunteers from the Towns of Chilmark and West Tisbury have provided essential insights toward this effort. Of particular note has been the efforts of Dr. Kent Healy, a concerned citizen who has monitored and measured pond levels and flows over a multitude of years and Bill Wilcox (former MVC Water Resources Planner), who has spent countless hours reviewing data and information with MEP Technical Team members in support of the MEP analysis of Tisbury Great Pond. In addition, Chris Seidel, GIS Specialist from the MVC, provided essential 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 Tisbury Great Pond Embayment System is a complex estuary located within the Towns of Chilmark and West Tisbury on the island of Martha's Vineyard, Massachusetts with a southern shore bounded by water from the Atlantic Ocean (Figure I -1). The Tisbury Great Pond watershed is distributed entirely in the Towns of Chilmark and West Tisbury, with a large region of the upper watershed comprised primarily of "protected" forest land (e.g. Manuel F. Correllius State Forest, 5100 acres) and open space associated with the Martha's Vineyard Airport. Land-uses closest to an embayment generally have greater impact than those in the upper portions of the watershed, which can support attenuation of nitrogen during transport through natural aquatic systems (e.g. ponds, rivers, wetlands etc.) prior to discharge to the embayment. However, effective nutrient management for restoration of the Tisbury Great Pond System, will require consideration of all sources of nitrogen load throughout the entire watershed. That the open water basins and the entire watershed to the Tisbury Great Pond system is contained within two towns makes development and implementation of a comprehensive nutrient management and restoration plan a little more complex as the challenges are complicated by potentially conflicting municipal constraints and regulations, but also provides the advantages of shared stewardship.

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. The large number of sub-embayments (i.e. coves) to the Tisbury Great Pond System greatly increases the shoreline and decreases the travel time of groundwater (and its pollutants) from the watershed recharge areas to bay regions of discharge. As such, the Tisbury Great Pond system is particularly vulnerable to the effects of nutrient enrichment from the watershed, especially considering that circulation is mainly through wind driven mixing in the small tributary sub-embayments, the long shoreline of the pond and the only periodic flushing with "clean" Atlantic Ocean water. In particular, the Tisbury Great Pond system and its sub-embayments along the south shore of Martha's Vineyard are at risk of eutrophication (over enrichment) from nitrogen enriched groundwater and surface water flows and runoff from the watershed.

The Tisbury Great Pond Embayment System is a complex coastal open water embayment comprised of a large central basin and multiple sub-embayments (Town Cove, Pear Tree Cove, Tiah Cove, Deep Bottom Cove, Thumb Cove and Black Point Pond). The system is maintained as an estuary by the periodic breaching of the barrier beach with a single temporary inlet. The estuary only occasionally receives tidal waters from the Atlantic Ocean into its large lower main basin based on a schedule of openings set by the Towns. Floodwater from the Atlantic Ocean enters the large lower basin of the Pond and circulates through channels and across flats making its way up into Town Cove (the primary tributary cove in this system) as well as into Black Point Pond which is connected to the main basin of Tisbury Great Pond via a narrow channel (Figure I-2). The pond openings follow periods where pond level rises due to groundwater and surface water inflows and precipitation which creates a hydraulic head facilitating the opening process. At present the number and duration of pond openings plays a fundamental role in the maintenance of nutrient related water quality and habitat health throughout this estuary.

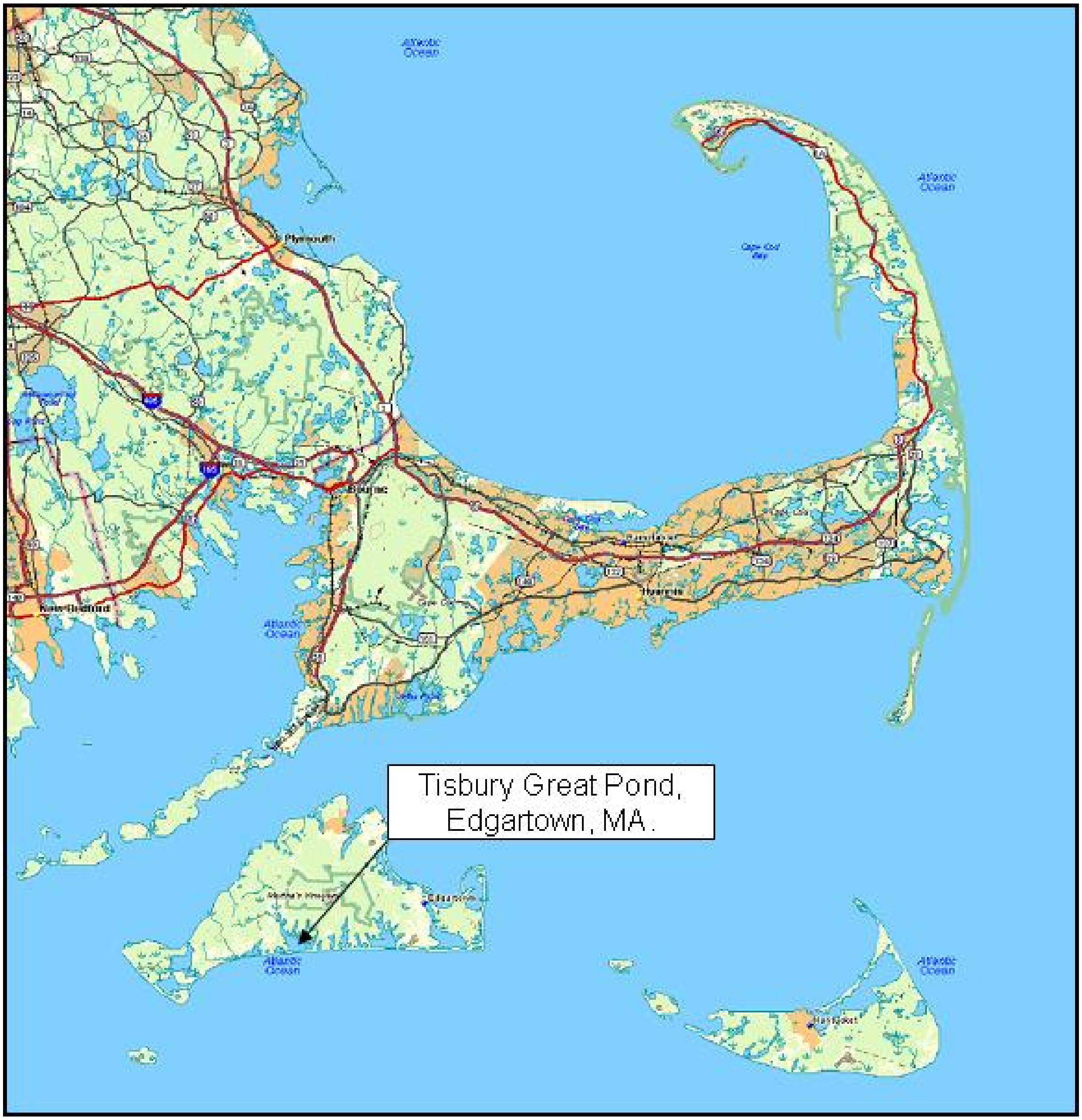

Figure I-1. Location of the Tisbury Great Pond Embayment System, Island of Martha's Vineyard, Town of Chilmark and West Tisbury, Massachusetts. Tisbury Great Pond is a great salt pond, maintained by periodic breaching of the barrier beach to lower nitrogen levels and increase salinity via tidal exchange with Atlantic Ocean waters.

The present Tisbury Great Pond Embayment System results from a complex geologic history dominated by glacial processes occurring during the last glaciation of the southeastern Massachusetts region. The late Wisconsinan Laurentide ice sheet reached its maximum extent and southernmost position about 20,000 years before present (BP), as indicated by the presence of terminal moraines on Martha's Vineyard and Nantucket and the southern limit of abundant gravel on the sea floor of Nantucket Sound and Vineyard Sound (Schlee and Pratt,

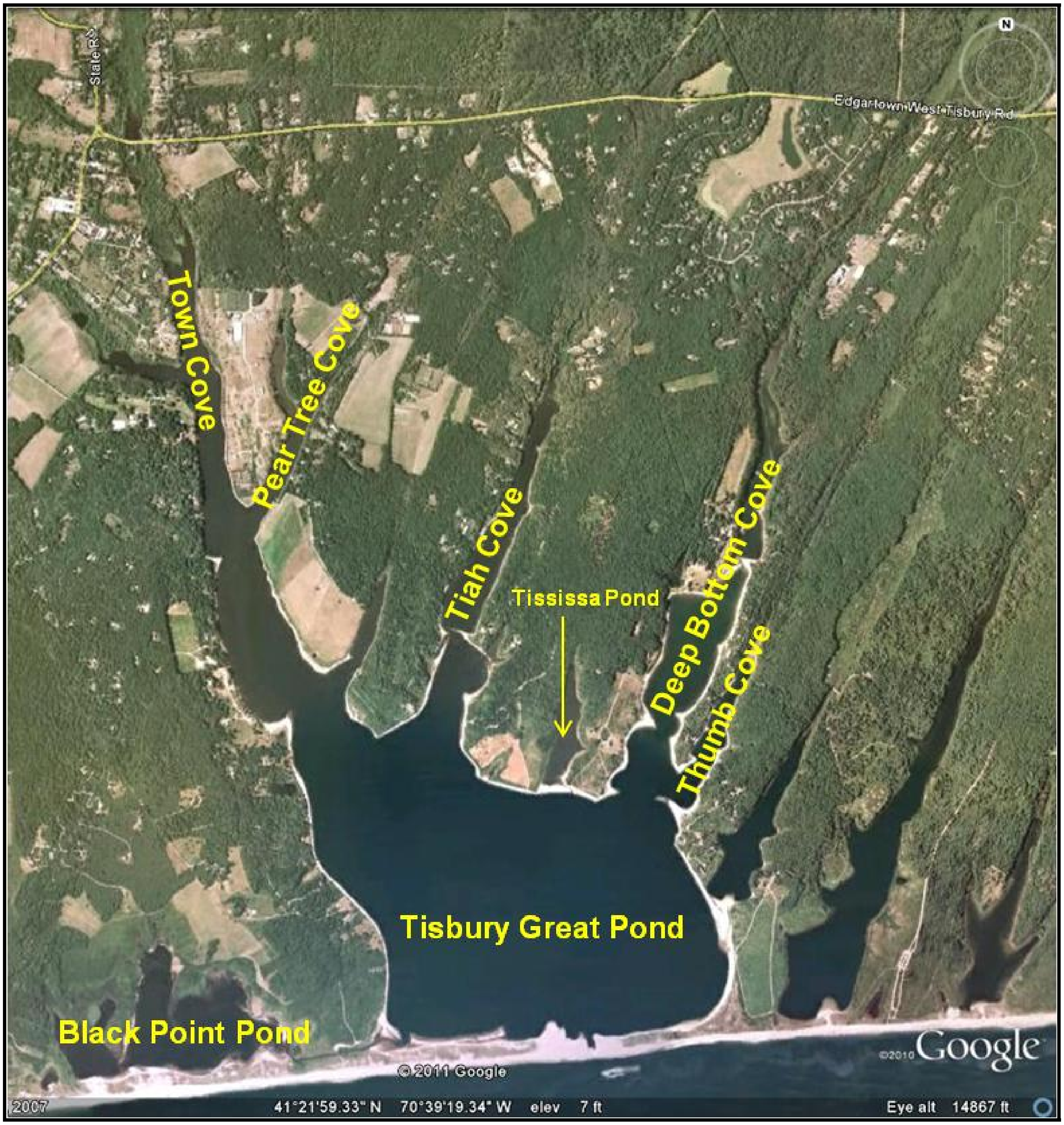

Figure I-2. Study region for the Massachusetts Estuaries Project analysis of the Tisbury Great Pond Embayment System. Tidal waters enter the Pond through periodic breaching of the barrier beach to allow tidal exchanges with Atlantic Ocean waters. Freshwaters enter from the watershed primarily through direct groundwater discharge as well as surface water inflows via Mill Brook and the Tiasquam River which discharge to the head of Town Cove.

1970; Oldale, 1992; Uchupi et al., 1996). The lobate ice front was comprised of the Buzzards Bay lobe that deposited the moraine along the western part of Martha's Vineyard, the Cape Cod Bay lobe that deposited the moraines across eastern Martha's Vineyard and Nantucket, and the South Channel lobe that extended east toward Georges Bank (Oldale and Barlow, 1986; Oldale, 1992). During the retreat of the ice sheet, approximately 18,000 years BP, the main part of Cape Cod was deposited as the Barnstable outwash plain and a glacial lake occupied Nantucket Sound. The glacial meltwater lake occupying what is now considered Nantucket Sound is likely to have had a profound effect on the geomorphology of Tisbury Great Pond. The tributary coves and main pond basin were likely formed by headward erosion by groundwater seepage fed from the glacial meltwater lake upgradient of present day Tisbury Great Pond. The process driving the formative headward erosion of the finger tributaries of Tisbury Great Pond is called spring sapping. This occurs when the water discharging from a spring to a wetland environment carries away loose sand and gravel and causes the spring and associated wetland to erode (and migrate) headward (up-gradient) carving a long straight valley which later fills with seawater with rising sea levels post-glaciation. The terrestrial eroded “valleys” that represent the finger like tributary coves of the Tisbury Great Pond system are relict, because most (with the exception of Town Cove) do not presently contain rivers or streams. They remain dry, except where their lower reaches have been drowned by the rise in sea level.

The formation of the Tisbury Great 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 Atlantic Ocean source waters. The ecological and biogeochemical structure of the pond is likely to have changed over time as the barrier beach naturally breached and closed as a function of high pond levels (freshwater inflow) and storm frequency and intensity. It is almost certain that its closed basin is geologically a recent phenomenon, and that the pond was more generally open during lower stands of sea level.

The Tisbury Great Pond embayment system periodically exchanges tidal water with the Atlantic Ocean through managed "breaching" of the barrier beach (South Beach). This Great Salt Pond is opened to tidal exchange by excavating a trench through the barrier beach about every 3 months if the water levels in the pond have risen sufficiently (by freshwater inflow) to provide sufficient head to erode the desired channel to the sea. In addition to insufficient pond level, openings can be delayed due to poor hydrodynamic conditions in the near shore ocean (wave height and direction can result in rapid in filling of the temporary inlet). Typically, pond water levels of one meters or greater above mean sea level are required, before a breach is attempted. Breaching of the pond is undertaken mainly as a means of controlling salinity levels in the pond and as a flood control measure to keep groundwater table levels low enough to keep the basements of houses bordering the pond from flooding during high pond levels and high water table periods of the year. Prior to the opening, given groundwater infiltration into the pond, the salinity is typically in the 6-10 ppt. range. Post opening of the pond, the salinity rises to >20 ppt. A narrow shallow channel, Crab Creek, was created between the main basin of Tisbury Great Pond and Black Point Pond to the west which provides for exchange of Black Point Pond water with the saline, low nutrient Atlantic Ocean waters during inlet openings. Both Black Point Pond and Tisbury Great Pond waters are continuously discharging to the ocean by seepage through the barrier beach when the inlet is closed and also exchange water in a limited way via the channel. The absence of continuous tidal exchanges between the estuary and Atlantic Ocean allows for a greater increase in nitrogen enrichment than in similar sized open estuaries per unit of watershed loading, resulting in increased sensitivity of this system to increased watershed nitrogen loading.

The Tisbury Great Pond Embayment System is a ~800 acre (depending on the water level in the pond) coastal salt pond, comprised of Tisbury Great Pond (743 acres) and Black Point Pond (64 acres). The pond is characterized by numerous tributary sub-embayments that are elongated and finger-like and extend into the coastal outwash plain built up during the last glacial period approximately 18,000 BP. The coves terminate in dry valleys, with the exception of Town Cove which receives surfacewater inflow from Mill Brook and the Tiasquam River, which are primarily groundwater fed streams. The dry valleys that extend up into the outwash plain deposits contain unique habitat characterized by dry, sandy soils that are exposed to salt spray and frequent frosts in winter. For the MEP analysis, the Tisbury Great Pond estuarine system was partitioned into two general sub-embayment groups: the 1) the main basin and 2) the tributary sub-embayments of Town Cove, Pear Tree Cove, Tiah Cove, Deep Bottom Cove/Thumb Cove and Black Point Pond (see Figure I-1).

The primary ecological threat to the Tisbury Great Pond embayment system as a coastal resource is degradation resulting from nutrient enrichment. Nutrient enrichment generally occurs through increases in watershed nitrogen loading resulting from changing land uses (typically conversion of pine/oak forest to residential development) and/or reduced tidal exchanges with offshore waters. Although the watershed and the Pond have some issues relative to bacterial contamination primarily within Town Cove and associated basins and Black Point Pond, fecal coliform contamination does not generally result in ecological impacts, but is focused on public health concerns related with consumption of potentially contaminated shellfish. The primary impact of bacterial contamination is the closure of shellfish harvest areas, rather than the destruction of shellfish and other marine habitats. In contrast, increased loading of the critical eutrophying nutrient (nitrogen) to the Tisbury Great Pond System results in both habitat impairment and loss of the resources themselves. Within the watershed of this great salt pond, nitrogen loading has been increasing as land-uses have changed over the past 60 years. The nitrogen loading to this system, like almost all embayments in southeastern Massachusetts and the Islands, results primarily from on-site disposal of wastewater and fertilizer applications (residential and agricultural), and to a lesser extent stormwater flows. This is discussed in detail in Section IV.1.

The Towns of Martha's Vineyard have been among the fastest growing towns in the Commonwealth over the past two decades and unlike the Town of Edgartown, which has a centralized wastewater treatment system with the site of discharge of its tertiary treated effluent being located in the Edgartown Great Pond watershed, the Towns of Chilmark and West Tisbury do not have such an effluent discharge to Tisbury Great Pond. Rather, the unsewered areas of the watershed to the Tisbury Great Pond Embayment System rely on privately maintained septic systems for on-site treatment and disposal of wastewater. As existing and likely increasing levels of nutrients impact the coastal embayments of the Towns of Chilmark and West Tisbury, water quality degradation will accelerate, with further harm to invaluable environmental resources of the Towns and the Island on the whole.

As the primary stakeholders to the Tisbury Great Pond Embayment System, the Towns of Chilmark and West Tisbury in collaboration with the Martha's Vineyard Commission (MVC) were among the first communities on Martha's Vineyard to become concerned over perceived degradation of their coastal embayments. Over the years, this local concern has led to the conduct of several studies (see Chapter II) of nitrogen loading to the system such as the Water Quality Study of Tisbury Great Pond, (Fugro-McClelland, 1992). Key in this effort has been the Tisbury Great Pond Water Quality Monitoring Program, spearheaded by the MVC and supported by private, municipal, county and state funds (most recently Massachusetts 604(b) grant program) with technical assistance by the Coastal Systems Program at SMAST-UMD. This effort provides the quantitative watercolumn nitrogen data (1995-2010) required for the implementation of the MEP's Linked Watershed-Embayment Approach used in the present study.

Since the initial results of the Water Quality Monitoring Program and the land-use studies indicated that parts of the Tisbury Great Pond system were presently impaired by land-derived nitrogen inputs, the Towns and Martha's Vineyard Commission (MVC) undertook additional site-specific data collection that has served to support MEP's ecological assessment and modeling effort. The common focus of the Towns of Chilmark/West Tisbury - MVC work related to the Tisbury Great Pond System has been to gather site-specific data on the current nitrogen related water quality throughout the estuary and determine its relationship to watershed nitrogen loads (e.g. Martha's Vineyard Commission Nutrient Load to Tisbury Great Pond, 2000). The multi-year water quality monitoring effort has provided the baseline information required for determining the link between upland loading, periodic tidal flushing, and estuarine water quality. The MEP effort builds upon the Water Quality Monitoring Program results and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the restoration of this embayment system. These critical nitrogen threshold levels and the link to specific ecological criteria form the quantitative basis for the nitrogen loading targets necessary for nitrogen management plans and the development of cost-effective alternatives for restoration of habitat impaired by nitrogen enrichment needed by the Towns of Chilmark and West Tisbury.

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 members of the Martha's Vineyard Commission. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns of Chilmark and West Tisbury 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 Tisbury Great Pond System and its associated watershed have been significantly altered by human activities over the past ~100 years. As a result, the present nitrogen "overloading" appears to result partly from alterations to its ecological systems. These alterations subsequently affect nitrogen loading within the watershed and influence the degree to which nitrogen loads impact the estuary. Therefore, restoration of this system should focus on managing nitrogen through both management of nitrogen loading within the watershed and restoration/management of processes which serve to lessen the amount or impact of nitrogen entering the estuary.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The nutrients are primarily related to changes in watershed land-use associated with increasing population within the coastal zone over the past half century. Many of Massachusetts' embayments have nutrient levels that are approaching or are currently over their ability to assimilate additional nutrient inputs without decline in their ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities and the food chain which they support. At higher levels, nitrogen loading from surrounding watersheds causes aesthetic degradation and inhibits even recreational uses of coastal waters. In addition to nutrient related ecological declines, an increasing number of embayments are being closed to swimming, shellfishing and other activities as a result of bacterial contamination. While bacterial contamination does not generally degrade the habitat, it restricts human uses. However like nutrients, bacterial contamination is frequently related to changes in land-use as watersheds become more developed. The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the culture, economy, and tax base of Massachusetts's coastal communities.

The primary nutrient causing the increasing impairment of the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within Southeastern Massachusetts alone, almost all of the municipalities (as is the case with the Towns of Chilmark and West Tisbury) 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) for those estuarine systems that are presently impaired by nitrogen enrichment or which will become impaired as build-out of their watershed continues. . Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an outline of an implementation plan. For this project, the MassDEP recognizes that there are likely to be multiple ways to achieve the desired goals, some of which are more cost effective than others and therefore, it is extremely important for each Town to further evaluate potential options suitable to their community. As such, MassDEP will likely be recommending that specific activities and timelines be further evaluated and developed by the Towns (sometimes jointly) through the Comprehensive Wastewater Management Planning process.

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

The major MEP nitrogen management goals are to:

- provide technical analysis and supporting documentation to 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 related health and nutrient sensitivity of each of the 89 embayments in southeastern Massachusetts
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment's model "alive" to address future municipal needs.

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

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

The Linked Model has been applied for watershed nitrogen management in approximately 60 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

I.2 NUTRIENT LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In sandy glacial outwash aquifers, such as in the watershed to the Tisbury Great Pond System, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer minerals (Weiskel and Howes 1992). Since even Martha's Vineyard and Cape Cod "rivers" are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems on Cape Cod (DeSimone and Howes 1998, Weiskel and Howes 1992, Smith *et al.* 1991) and Martha's Vineyard. The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). The estuarine reaches within the Tisbury Great Pond Embayment System follow this general pattern, with the Redfield Ratio (N/P) ranging from 2-7 for the main basin and coves of Tisbury Great Pond and 6 for Black Point Pond, indicating that the primary nutrient of eutrophication in the system is nitrogen.

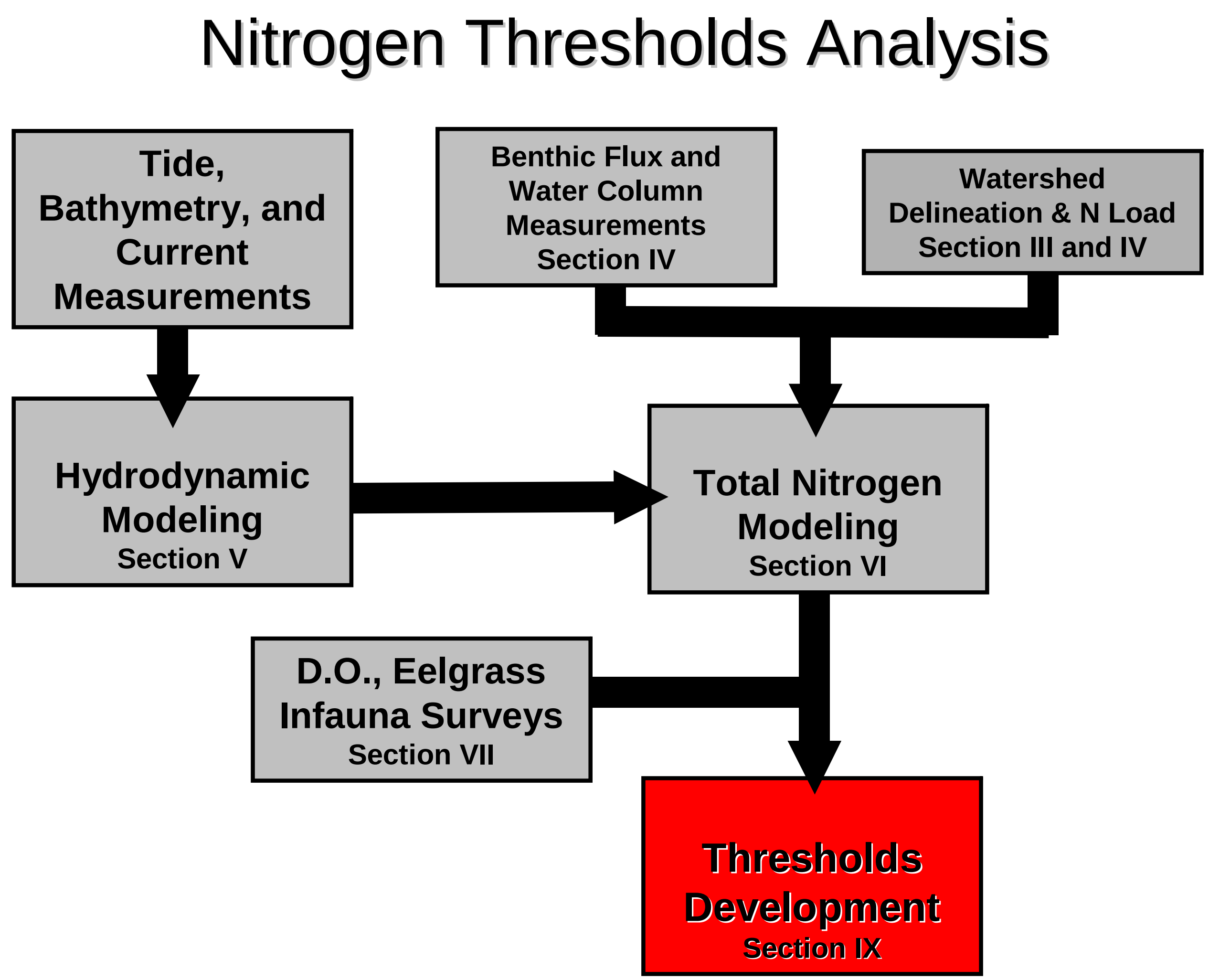

Figure I-3. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

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

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

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

Unfortunately, almost all of the estuarine reaches within the Tisbury Great Pond System are near or beyond their ability to assimilate additional nutrients without impacting their ecological health. Nitrogen levels are elevated throughout this Great Salt Pond and eelgrass beds have been lost over the past ~50 years as indicated by the MassDEP Eelgrass Mapping Program and as confirmed by the MEP Technical Team during the summer and fall of 2005. Nitrogen related habitat impairment within the Tisbury Great Pond Estuary shows a moderate gradient of high to low moving from the inland reaches to the barrier beach, primarily related to the configuration of the estuary and its depositional basins. The result is that nitrogen management of the primary sub-embayments to the Tisbury Great Pond system is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed “eutrophication” and in certain instances can occur naturally over long periods of time. When the nutrient loading is rapid and primarily from human activities leading to changes in a coastal watershed, nutrient enrichment of coastal waters is termed “cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to this embayment system and contributed to its decline in ecological health, the Tisbury Great Pond basins, like those analyzed by the MEP in Edgartown Great Pond, are especially sensitive to nitrogen inputs, because of the lack of continuous tidal exchange. The quantitative role of the discontinuous tidal exchange of this system, as a natural process, was also considered in the MEP nutrient threshold analysis. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a "pristine" system.

I.3 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important "boundary conditions" (e.g. watershed derived and offshore nutrient inputs) for water quality modeling of the Tisbury Great Pond Embayment 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 Tisbury Great Pond Embayment System, including the tributary sub-embayments of Town Cove, Pear Tree Cove, Tiah Cove, Deep Bottom Cove/Thumb Cove, and Black Point Pond. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents during breaching events and water elevations was employed for the system. Once the hydrodynamic properties of each estuarine basin were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

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 MVC/MEP refined watershed and subwatershed delineations are based on 1) water table contours measured in a few locations (*e.g.*, Wilcox, 1996) and modeled throughout the outwash plain and 2) USGS topographic maps in the western moraine. Almost all nitrogen entering the Tisbury Great Pond System is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Atlantic Ocean source waters and throughout the Tisbury Great Pond system were taken from the Water Quality Monitoring Program (a coordinated effort between the Towns of Chilmark and West Tisbury, Martha's Vineyard Commission and the Coastal Systems Program at SMAST). Measurements of salinity and nitrogen and salinity distributions throughout the estuarine waters of the system (1995-2010) were used to calibrate and validate the water quality model (under existing loading conditions).

I.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Tisbury Great Pond System for the Towns of Chilmark and West Tisbury. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Nitrogen loads from the watershed and sub-watersheds surrounding the estuary were derived from the Martha's Vineyard Commission data and offshore water column nitrogen values were derived from an analysis of monitoring stations in the Atlantic Ocean (Section IV and VI). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Section VI. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of 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 Town in developing a variety of alternative nitrogen management options for this system. Finally, any additional analyses of the Tisbury Great Pond System beyond the standard suite offered by the MEP may be undertaken relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of dredging/breach options to improve nitrogen related water quality. The results of the nitrogen modeling for each scenario, should they be undertaken are typically presented in Section VIII.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

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

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

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

Tisbury Great Pond Watershed Study (1989) – This report was prepared for the Towns of Chilmark and West Tisbury Planning Departments by Robert E. Woodruff and Craig E.

Saunders as a precursor to a diagnostic/feasibility study of Tisbury Great Pond (Phase I Project) to be completed under the Massachusetts Clean Lakes Program. Due to lack of funding from the Commonwealth, the Phase I Project was never undertaken, however, an analysis of the watershed was completed. While the report does not directly address issues of habitat impairment resulting from nutrient enrichment of the Tisbury Great Pond system, it does offer some insights into potential sources of nutrient loading that existed ~25 years ago. The main objectives of this watershed investigation were as follows: 1) describe current land use practices and build-out projections in the areas of Chilmark and West Tisbury that constitute the Tisbury Great Pond watershed, 2) provide estimates of present loading and nutrient (nitrogen) loading at watershed build-out based on the land-use analysis and 3) make recommendations to the Towns of Chilmark and West Tisbury regarding watershed management strategies that could be effective in safeguarding the Tisbury Great Pond resource. In this report the authors determined that under "present" (e.g. 1988) land-use conditions, approximately 39,758 pounds/year (18,033 kg/y) of nitrogen would be generated in the Tisbury Great Pond Watershed and the total load was generally attributable to direct precipitation to the pond (55%), septic systems (22%), fertilizers (18%) and agriculture (4%). Under buildout conditions, the authors estimated that watershed nitrogen loading would increase to approximately 78,092 pounds/year (35,421 kg/y) and that the sources of nitrogen were direct precipitation to the pond (31%), septic systems (38%), fertilizers (29%) and agriculture (2%). Acknowledging the critical role that nutrients play in the eutrophication of coastal ponds like Tisbury Great Pond, Woodruff and Saunders recommended the establishment of a long-term water quality monitoring program to track potential impairment of the system as watershed nitrogen inputs increased over time. The study indicated that based on a 1988 nutrient analysis of Tisbury Great Pond (Priesters Pond Environmental Impact Statement) Tisbury Great Pond may be mesotrophic. Saunders defines mesotrophic as a pond "midway in progression towards becoming eutrophic."

Water Quality Study of Tisbury Great Pond (1992). - This report was prepared by Fugro-McClelland (East) for the Towns of Chilmark and West Tisbury and the overall objectives of the investigation was to establish existing water quality conditions in the pond as a baseline for future investigations as well as to characterize the distribution of bacteria in the pond and potential sources. This particular study was also tasked to quantify functional attributes of the pond system such as the influence of groundwater, the tributaries, circulation, tidal influence and flushing. Field activities were conducted from January to December of 1991 and during that time a bathymetric survey was also completed. Field measurements and sampling of Tisbury Great Pond were undertaken monthly for one year and samples were collected from six (6) stations throughout the pond. One station was located in the main basin of the pond close to the barrier beach while the other five stations were distributed amongst the tributary coves. During the study period, sampling was also undertaken in association with planned breaches of the barrier beach in order to quantify the extent to which tidal exchange during an opening effected water quality, salinity, flushing and circulation. Samples were assayed for nutrients (ammonia, nitrate, Total Kjeldahl Nitrogen (TKN) and total phosphorous). The investigators concluded that nutrient levels within Tisbury Great Pond were “somewhat elevated in comparison to historical data from other coastal ponds on Martha’s Vineyard.”

Over the course of the year long study, measures of environmental parameters such as salinity, conductivity, chloride, pH and alkalinity were also obtained to aid in characterizing the baseline conditions of the pond during both periods when the pond was open to tidal exchange and when it was not. As expected, when the pond was opened, the waters of the lower basin were heavily influenced by the fully marine waters entering from the Atlantic Ocean and salinity, pH and alkalinity increased. Furthermore, as water levels in the pond dropped during an open period, brackish waters from the tributaries tended to flow towards the temporary inlet, which resulted in a temporary freshening due to accelerated groundwater inflow and on-going surface water inflows from the Tiasquam River and Mill Brook. This freshening was temporary as mixing with saline waters of the main basin took place. The investigators determined that when the pond is closed it is a well mixed homogenous system with brackish waters. Finally, the report offered some preliminary recommendations for management of the pond: (a) vegetated buffer strips should be maintained or restored as a mechanism for capturing pollutants such as bacteria and nutrients, (b) groundwater should be further analyzed and characterized to improve the nutrient baseline of the pond, (c) a scaled down water quality monitoring program should be continued to extend the data set and better elucidate trends in water quality.

Tisbury Great Pond Watershed Study (1996) – This study of the Tisbury Great Pond watershed was undertaken by the Martha's Vineyard Commission (Mr. William Wilcox) in collaboration with Martha's Vineyard Shellfish Group and the UMASS Extension with support from the Edey Foundation. The effort was the next step towards gaining a better understanding of nutrient loading from the Tisbury Great Pond watershed to support development of nutrient management strategies to protect/restore the habitat quality within the receiving salt pond system. This report builds on some of the recommendations and findings of the Fugro-McClelland (East) 1992 report described above.

The 1996 Watershed Study was devoted to establishing the water quality of the groundwater and surface water streams discharging to the salt pond. Water quality analysis was conducted on newly installed monitoring wells, streams and existing private wells during 1994 and early 1995. Based upon new information on water table contours north of the Pond, the prior watershed delineation was refined and the watershed area was determined to be 10,841 acres. The results of the water sampling and analysis were used to estimate the nitrogen load discharged to Tisbury Great Pond via groundwater, streams and acid rainfall. Based on water sampling results and approximation/measurement of freshwater flow from the watershed, it was determined that a total of 8,509 kilograms per year was loaded to Tisbury Great Pond[1]. Alternatively, a range of standard figures for septic effluent on a per capita basis, lawns and farms where fertilizer is applied were employed to estimate nutrient loading to Tisbury Great Pond. This approach yielded a range of 7,551 to 11,648 kilograms per year that agreed with the load as determined by the water quality test results (8,509 kg/yr). From these results, the 1996 study concluded that the groundwater generated within the Tisbury Great Pond watershed carries about 71 percent of the nitrogen introduced to the Pond, the streams carry 20 percent and rainfall provides 10 percent. Projections were also made regarding the degree to which nutrient loading to the pond system would increase under build-out conditions. It was projected that nutrient loading to the pond at build-out could range from a high of 17,307 to a low of 10,622 kilograms per year.

Finally, a nitrogen loading limit for Tisbury Great Pond was estimated from a generic formula at between 12,000 and 15,000 kilograms per year. The limit was based upon the Buzzards Bay Project (BBP) Approach (Costa et al. 1999). The results suggested that the pond was near (Woodruff and Saunders 1989) or might exceed this threshold at build-out (present 1996 study). While this study was forward looking at the time, the underlying BBP model available at the time could not be calibrated or validated and did not assess the habitats within the estuary itself. Therefore, while the effort was thoughtful and well executed, the model was not sufficiently robust to accurately represent the Tisbury Great Pond System for the purposes of establishing nitrogen loading targets for estuarine management planning. Similar results

[1] The nitrogen load to Tisbury Great Pond from this 1996 study is ~1/2 the assessment (18,033 kg/yr) by Woodruff and Saunders (1989) noted above.

have been observed for other estuaries, e.g. Edgartown Great Pond and Oak Bluffs Harbor (Howes et al. 2002). As a result the authors concluded in the 1996 report, "[w]hile not tailored to the Great Pond, the formula results when compared with the build-out projections strongly suggest the need to move forward in deriving a better nitrogen loading limit for the Pond." The author also concluded that the Pond may vary between being nitrogen deficient to being phosphorus deficient. This will be considered under the MEP assessment of Tisbury Great Pond in order to inform the development of appropriate nutrient management alternatives.

Hydrology of Tisbury Great Pond - Martha's Vineyard, Massachusetts (2009) -- This report was prepared by a local concerned citizen, Dr. Kent A. Healy to make available hydrology information and analysis related to Tisbury Great Pond. The hydrology report provides in-depth information regarding groundwater flow, as well as the influence of periodic barrier beach breaching which is performed to control pond levels and water quality. The detailed long-term pond elevation measurements proved invaluable for validating the groundwater flow computed through the MEP analysis and historical water elevations within the pond. In combination with the total nitrogen and salinity measurements taken at various locations within the pond, the water elevation data provided baseline information regarding the long-term relationship between water level, dilution and nutrients. In addition the documentation of the historical frequency of barrier breaching, the duration of each opening provided critical information required to assess the relative "success" of the various inlet breach events and provides a benchmark for developing different opening scenarios. Overall, this site-specific assessment provides high-quality data that could be used to support the MEP Linked Watershed-Embayment Modeling Approach for the Tisbury Great Pond/Black Point Pond System.

Nutrient Loading to Tisbury Great Pond (2000) – This report was prepared by the Martha's Vineyard Commission. Specifically, Jo-Ann Taylor designed the project with the assistance of Mr. William Wilcox, and served as principal investigator, author, and MVC project quality assurance officer. The Tisbury Great Pond Riparian Owners contributed funds for the water sampling program. Surface water quality samples were analyzed by the Coastal Systems Analytical Facility within the School for Marine Science and Technology, University of Massachusetts at Dartmouth. This project was also financed partially with Federal Funds from the Environmental Protection Agency (EPA) to the Massachusetts Department of Environmental Protection (the Department) under a section 604(b) Water Quality Management Planning Grant (# 99-02/604 – Nutrient Loading to Two Great Ponds).

The report is a refinement of the MVC 1996 watershed and loading analysis described above and was undertaken in response to continuing signs that Tisbury Great Pond was becoming impaired. At the time this report was undertaken, large areas of the pond had been closed to recreational and commercial harvest of shellfish because of fecal coliform contamination and the authors reported clear signs of eutrophication of the system, such as excessive growth of algae and mortality of oysters. The report provides yet another milestone in the characterization of the watershed and the associated nutrient loading to Tisbury Great Pond. The refined watershed nitrogen loading analysis estimated higher loading figures than those presented in the 1996 Tisbury Great Pond Watershed Study.

Based on the 2000 watershed analysis, when filled, Tisbury Great Pond and Black Point Pond together represent approximately 800 acres. The landside portion of the watershed includes 12,250 acres, of which an area of 6,214 acres is directly associated to recharge of the groundwater system whereas the remainder of the watershed (an area of 6,036 acres) is associated with both groundwater and surfacewater contributions to the pond. In 2000, the calculated nitrogen load to the pond from the watershed was approximately 13,443 kilograms per year, from the following sources in kilograms/yr: 1) Rain (5,589), 2) Septic Systems Residential (4,406), 3) Commercial (316), Farms (2,671), Lawns (461). Utilizing these loading figures as well as other information on the Tisbury Great Pond habitat and from the literature, the authors recommended a nitrogen loading limit of 15,000 kilograms per year from the entire watershed. As a point of comparison, the 1996 study recommended a nitrogen loading limit of between 12,000 and 15,000 kilograms per year. However, it should be noted that the loading limit was based upon an approach developed for embayments open to tidal exchange and which is inherently unverifiable (see above). Finally, the authors compared the "existing" loading limit with projected nitrogen loading under a variety of scenarios: 1) Nitrogen Load at Low Growth (15,491 kg/y), 2) Nitrogen Load at Moderate Growth (19,327 kg/y) and 3) Nitrogen Load at High Growth (23,204 kg/y). Ultimately, the authors concluded from the calculations that the proposed limit is quite close to the low growth scenario. The conclusion is further supported by the water quality sampling data from 1999. As a result of the watershed analysis, management recommendations were developed and are significant as these are the precursors to the Massachusetts Estuaries Project Analysis. Management recommendations put forward in the 2000 report are as follows:

1) ADOPT 15,000 KILOGRAMS AS AN ANNUAL LOAD LIMIT FOR THE WATERSHED

- Measure and monitor chemical composition of local rainfall. Identify impacts of individual forms of nitrogen.
- Determine growth needs and desires for the watershed area in both towns.
- If new growth is appropriate for the towns' needs, restrict new septic systems to those with advanced nitrogen removal.
- Revise zoning and board of health regulations to support the 15,000 kg limit. Consider a watershed-wide DCPC to develop and implement those regulations.
- Maximize acquisition or protection of much of the remaining open space in the watershed.
- Focus water quality planning on protection of immediate shoreline from direct contamination by farm animals, rather than on overall nitrogen load.
- Encourage low-nitrogen farm activities where practical, such as in conjunction with open space ventures.
- Educate homeowners and professional landscapers about using native plants and about fertilizer impacts.

2) FURTHER ASSESSMENT AND MONITORING

- Continue water sampling. Plan a five-year annual program. Include weather data from the Martha's Vineyard Coastal Observatory in analysis. Include some continuous recorded logs of dissolved oxygen over several daily cycles.
- Further investigate dynamics of relationship between Tisbury Great Pond and Black Point Pond.
- Measure and monitor chemistry of local rainfall.
- Differentiate between "stream shed" and "ground watershed" management needs.

3) CONTINUE MAINTENANCE BREACHING

- Continue breaching as practiced by the Tisbury Great Pond Riparian Owners, as authorized by Chapter 203 of the Acts of 1904.
- Consider enhancement of inlet breaching by dredging in the pond.

4) PROMOTE SHELLFISH AND HERRING

- Promote shellfish as nutrient consumers, along with herring. Ensure that their habitats are protected.

MVC/Town of Oak Bluffs and Edgartown Water Quality Monitoring Program (1995-2010) – A significant record of baseline water quality throughout the Tisbury Great Pond System has been developed over the past 15 years, in large part due to the efforts by the Martha's Vineyard Commission as well as the Trustees of Reservations (2000). The Martha's Vineyard Commission partnered with SMAST-Coastal Systems Program scientists in 1995 to develop and implement a nutrient related water quality monitoring program of the estuaries of Martha's Vineyard, inclusive of Tisbury Great Pond in the Towns of Chilmark and West Tisbury. Sample analysis was conducted by the Coastal Systems Analytical Facility at SMAST-UMD with the exception of 2 years (2001 and 2002) when samples where analyzed by a laboratory at the University of Washington. It should also be noted that some of the samples in the water quality database where obtained from stations established by the Trustee's of Reservations. These samples were mainly samples collected in 2000 and are from some stations that differed in location from the samples collected by the Martha's Vineyard Commission (though some station overlap exists). The Martha's Vineyard Commission working with volunteers, interns and the Town of Chilmark Shellfish Department coordinated and executed the water quality surveys of the Tisbury Great Pond System. For Tisbury Great Pond as well as the other estuarine systems of Martha's Vineyard, the focus of the water quality monitoring effort has been to gather site-specific data on the current nitrogen related water quality throughout the estuarine reach of a given system to support assessments of habitat health. This baseline water quality data are a prerequisite to entry into the MEP and the conduct of its Linked Watershed-Embayment Approach. The water quality monitoring program was initiated in 1995 and along the way supported by funds obtained from the Massachusetts 604B Grant Program (1999) and the Tisbury Great Pond Riparian Owners. The monitoring program has continued uninterrupted through the summer of 2010. Throughout the water quality monitoring period, sampling was undertaken between 4 and 6 times per summer between the months of June and September. The MVC/Town based Water Quality Monitoring Program for Tisbury Great Pond developed the baseline data from sampling stations distributed throughout the main basin as well as the major tributary coves such as Town Cove, Tiah Cove and Deep Bottom Cove as well as water flowing out of Black Point Pond (Figure II-1). Additional sampling stations were established by the Trustee's of Reservations in 2000 and are depicted in Figure II-2. As remediation plans for this and other various systems on Martha's Vineyard are implemented throughout the towns, monitoring will have to be resumed or continued to provide quantitative information to the towns relative to the efficacy of remediation efforts. As Tisbury Great Pond is only periodically open to tidal exchange, continued monitoring is essential to provide the necessary feed back on the "success" of the openings and the need to refine the approach or schedule for breaching the barrier beach as a means of managing nutrients within this embayment.

Implementation of the MEP Linked Watershed-Embayment Approach incorporates the quantitative water column nitrogen data (1995-2010) gathered by the Water Quality Monitoring Program and watershed and embayment data collected by MEP Technical Staff. The MEP effort also builds upon previous watershed delineation and land-use analyses as well as eelgrass surveying by the MassDEP Eelgrass Mapping Program and MEP Technical Staff. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Tisbury Great Pond Embayment System. The MEP has incorporated all appropriate data from previous studies to enhance the determination of nitrogen thresholds for the Tisbury Great Pond System and to reduce costs of restoration for the Towns of Chilmark and West Tisbury.

Regulatory Assessments of Tisbury Great Pond Resources - The Tisbury Great Pond System (inclusive of Black Point Pond) contains a variety of natural resources of value to the citizens of Chilmark and West Tisbury as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP gathers the available information on these resources as part of its assessment, and presents them here (Figures II-3 through II-6) for reference by those providing stewardship for this estuary. For the Tisbury Great Pond Estuary these include:

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

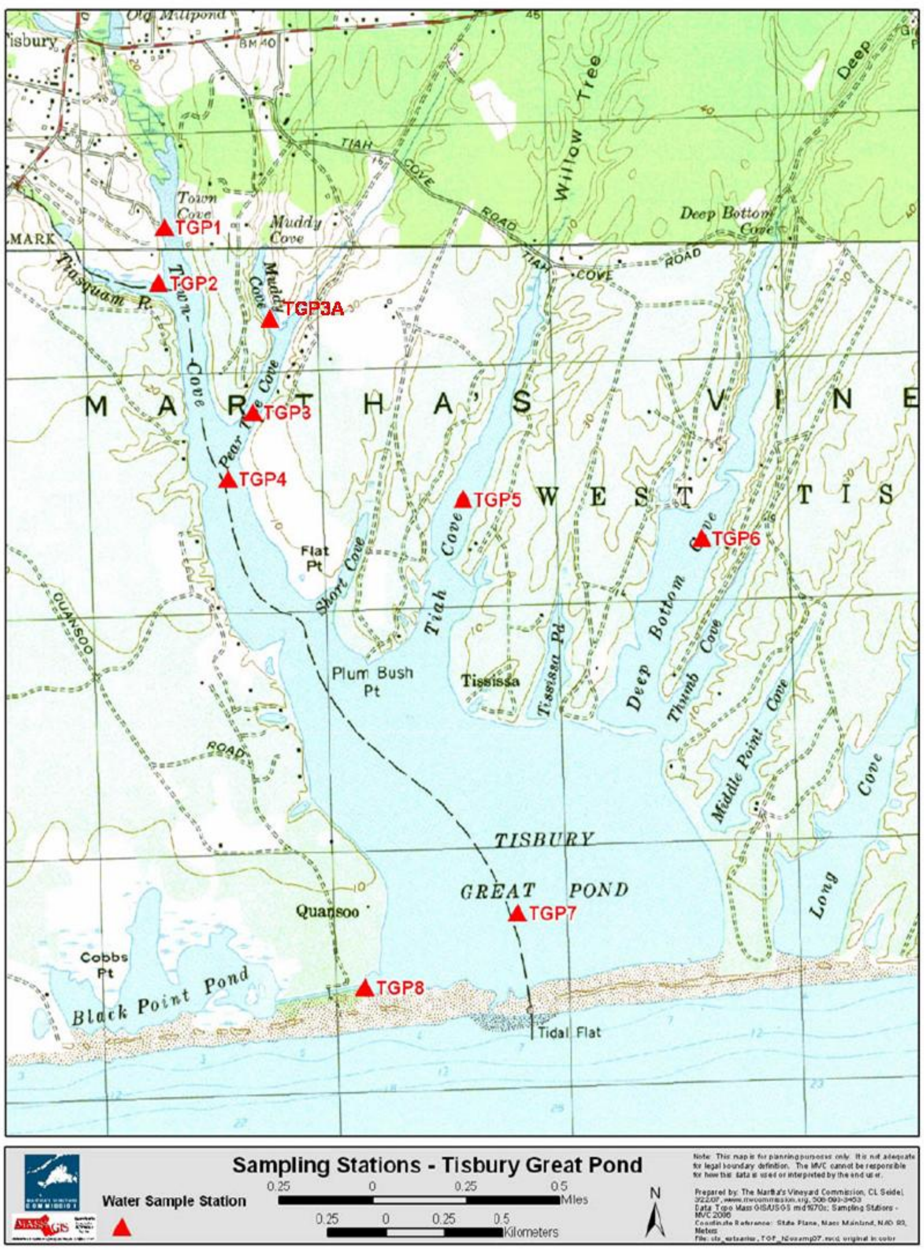

Figure II-1. MVC/Town of Chilmark / Town of West Tisbury Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the MVC/SMAST/Town and volunteers.

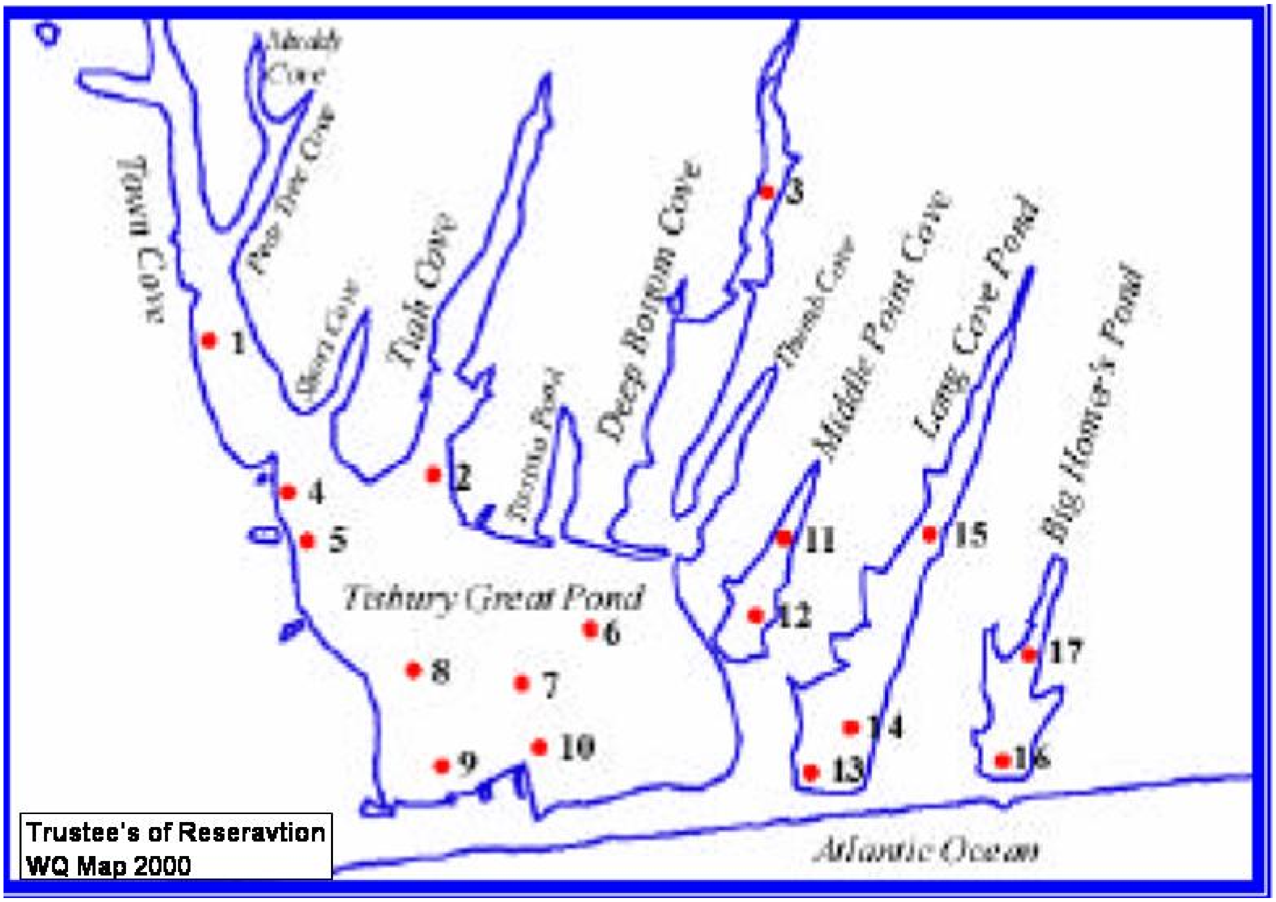

Figure II-2. Trustee's of Reservation Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by Martha's Vineyard Commission and volunteers

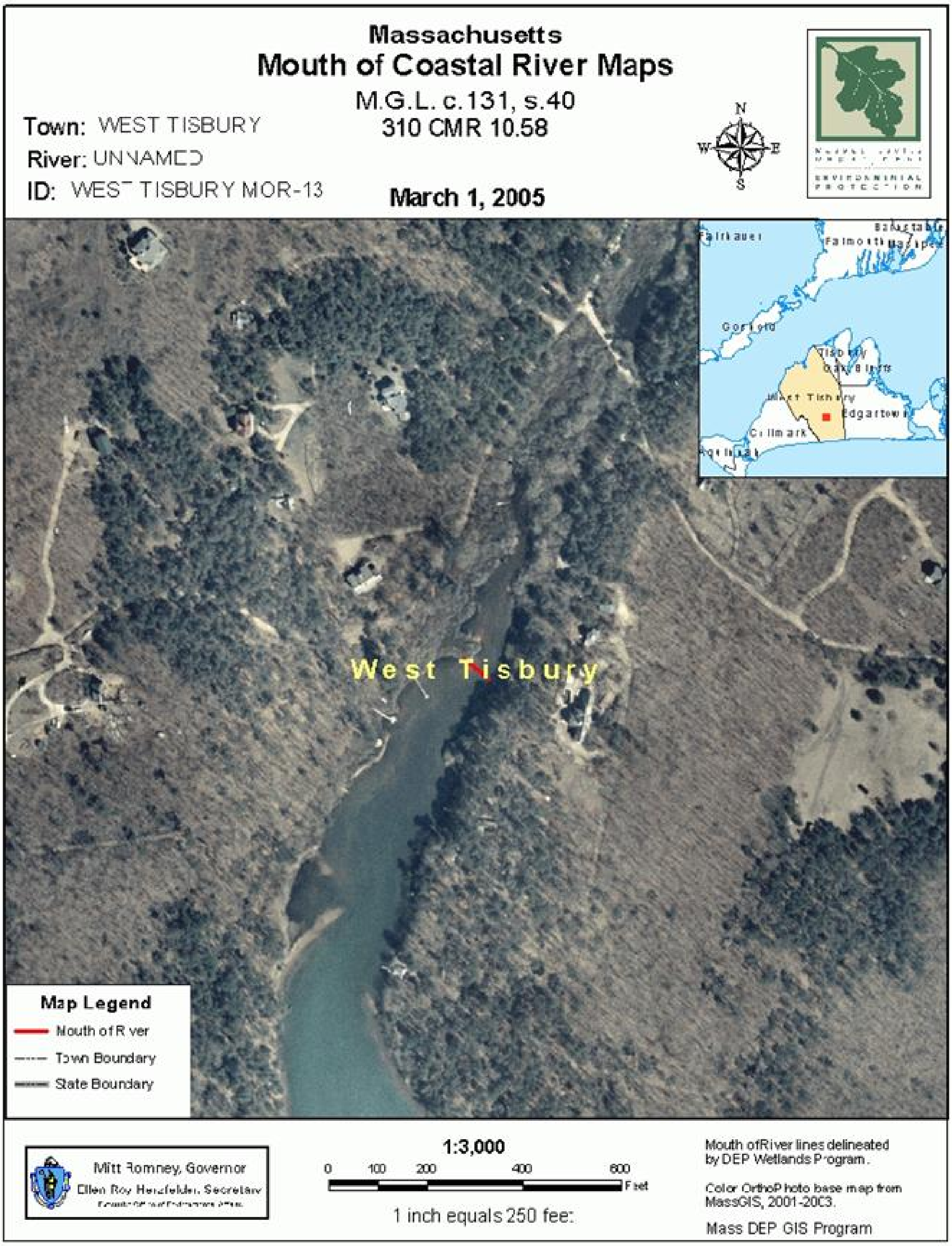

Figure II-3a. Regulatory designation for the mouth of "River" line under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

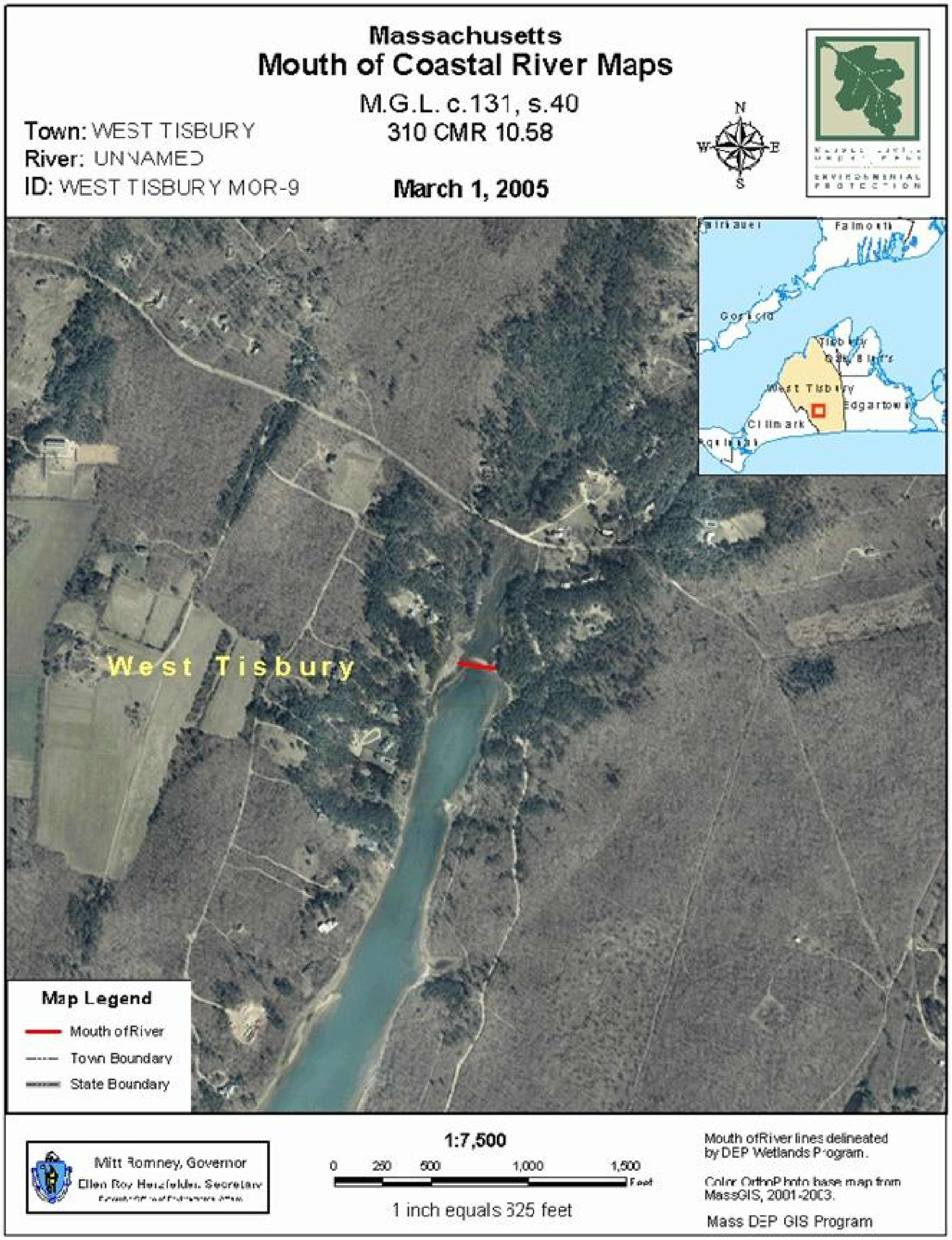

Figure II-3b. Regulatory designation for the mouth of "River" line under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

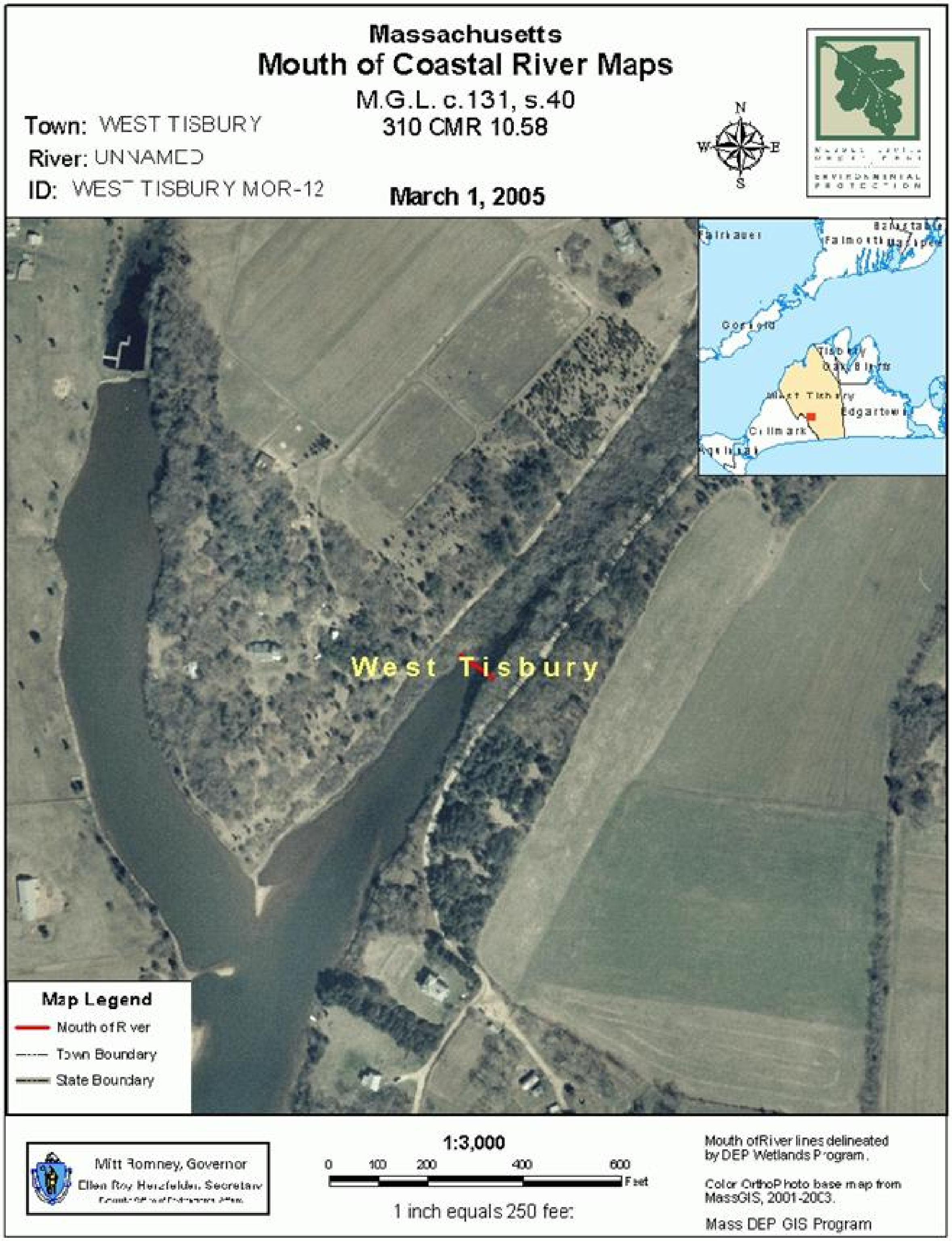

Figure II-3c. Regulatory designation for the mouth of "River" line under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

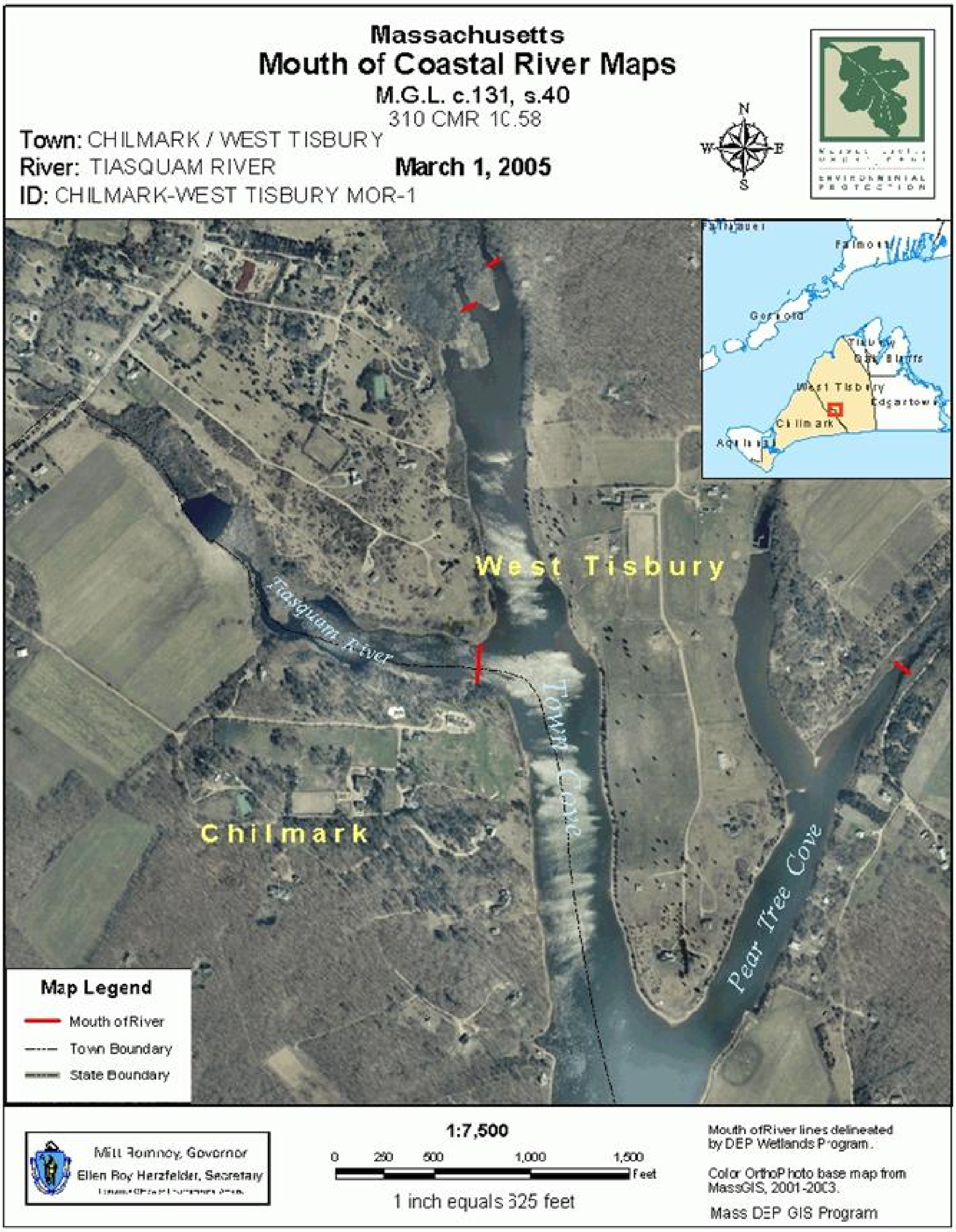

Figure II-3d. Regulatory designation for the mouth of "River" line under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

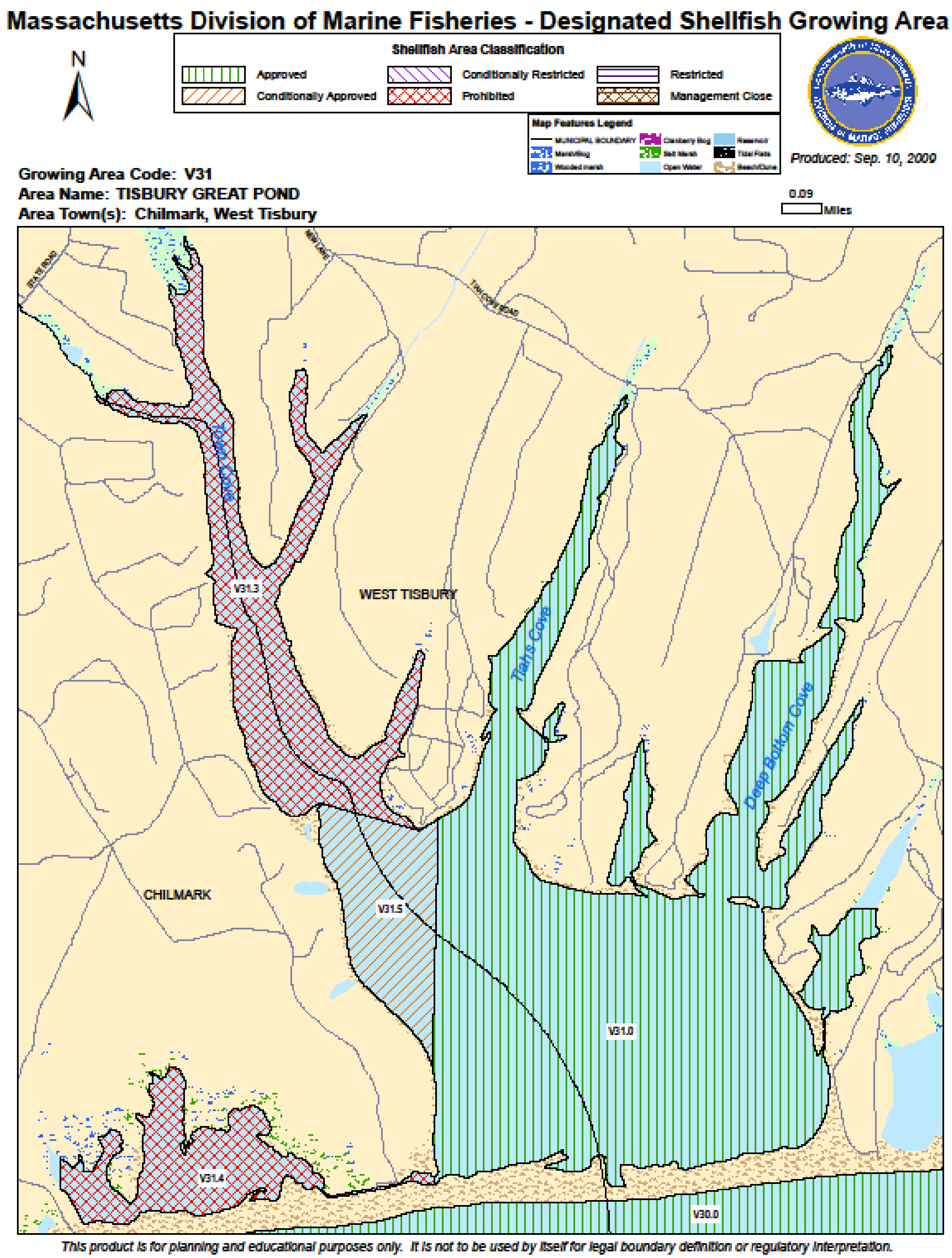

Figure II-4. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

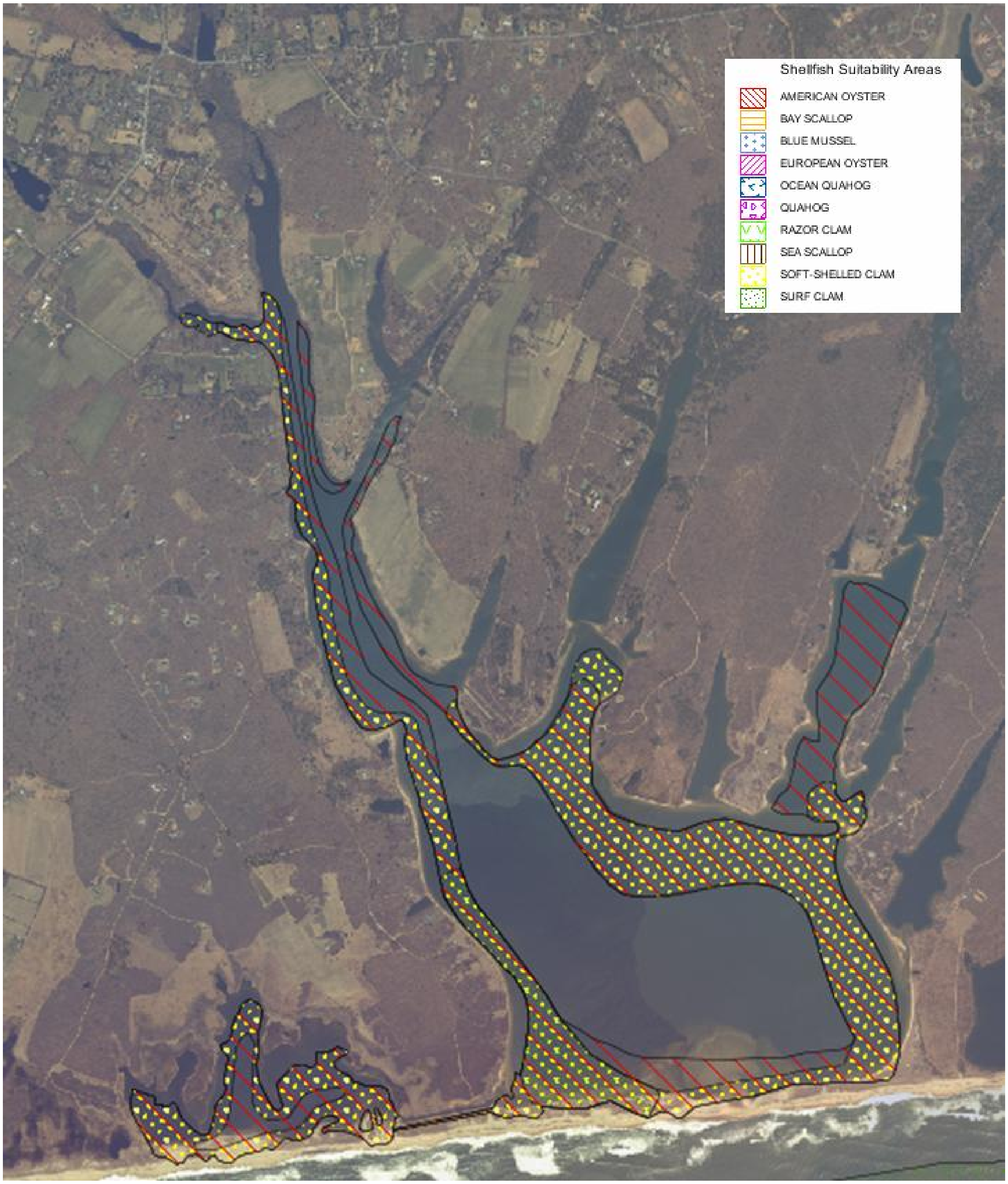

Figure II-5 Location of shellfish suitability areas within the Tisbury Great Pond Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean that a shellfish population is "present".

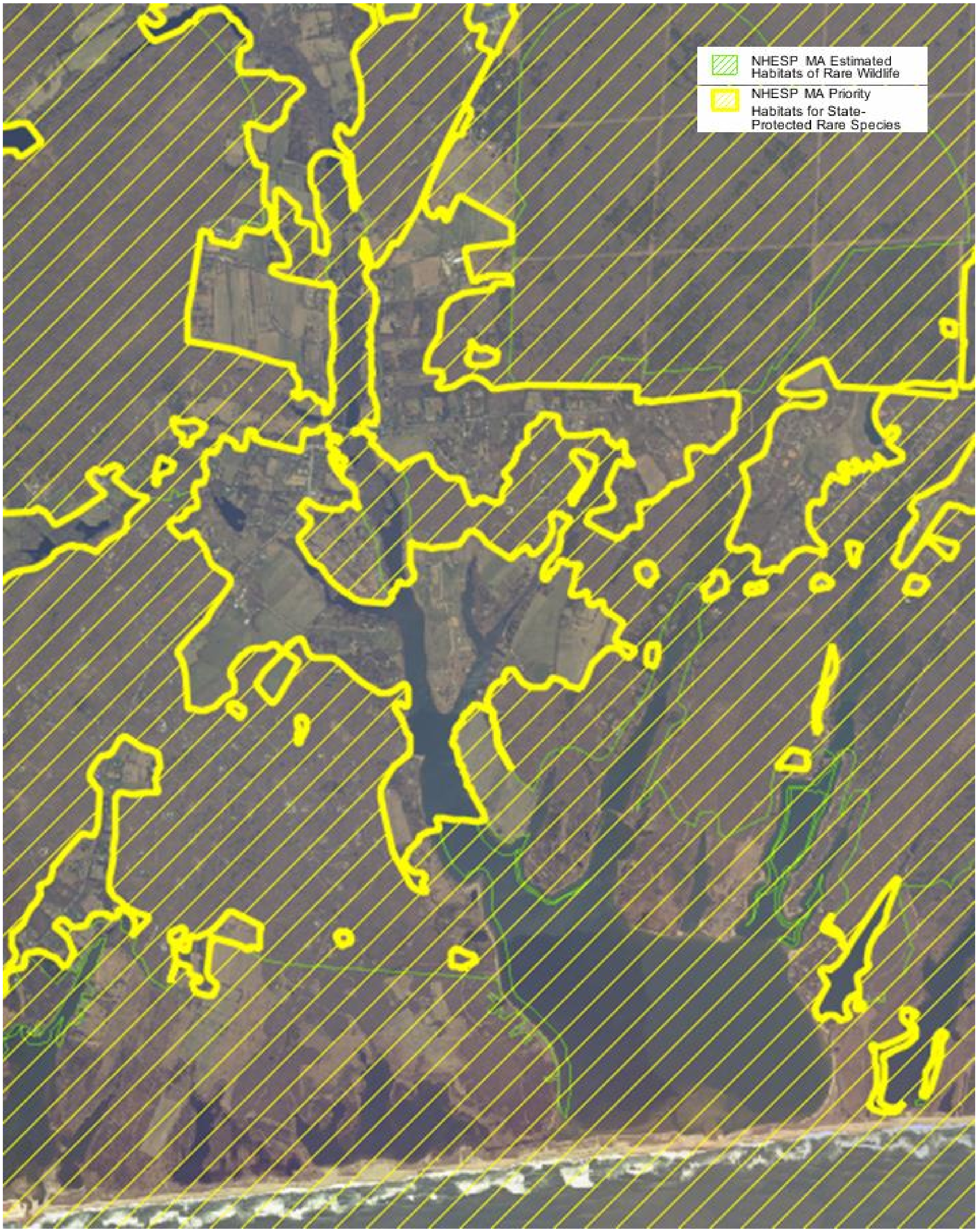

Figure II-6. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Tisbury Great Pond and Black Point Pond Estuary as determined by the Massachusetts Natural Heritage and Endanger Species Program (NHESP).

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

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

The relatively porous deposits that comprise most of the Vineyard outwash plain and the eastern moraine create a hydrologic environment where watersheds are usually better defined by elevation of the groundwater and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). Delaney (1980) and subsequent characterizations have indicated that these characteristics also apply to the eastern moraine. Limited water table measurements and hydrogeologic borings in the western moraine, however, have indicated that surface topography is a more appropriate basis for watershed delineation in this portion of the island (W. Wilcox, personal communication).

Freshwater discharge to estuaries is usually composed of surface water inflow from streams, which receive much of their water from groundwater base flow, especially in aquifer systems like the Vineyard outwash plain, 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 discharging directly into an estuary via groundwater seepage. In the Tisbury Great Pond Embayment watershed, the majority of freshwater watershed enters through groundwater (~75%), with a smaller proportion (25%) through the surface water inflows of Mill Brook and Tiasquam River (see Section IV.2).

Tisbury Great Pond and its watershed are mostly located within the island's main outwash plain, but the western and northern boundaries of the watershed are located within the more complex, western moraine. The watersheds utilized in the MEP assessment are largely based on delineations created and used by the Martha's Vineyard Commission (MVC). The portions of the watershed within the outwash plain have been delineated based on regional groundwater contours (Delaney, 1980) and with more refined water level readings in selected areas (Wilcox, 1996). A 1991 United States Geological Survey (USGS) regional water table map of the outwash plain generally showed the same water table configuration as the 1980 contours (Masterson and Barlow, 1996). Masterson and Barlow used the 1991 water table readings as guidance for construction of a regional two-dimensional, finite-difference groundwater 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 characterizations of the hydrogeology, including the installation of numerous long-term monitoring wells, over the last few decades have provided the basis for subsequent activities, including the delineation and refinement of estuary watersheds. In 1994, Whitman and Howard produced a groundwater model with a domain that covered Martha's Vineyard eastern moraine and the outwash plain; this model was based on the publicly available USGS MODFLOW three-dimensional, finite difference groundwater model code. The Wilcox (1996) watershed delineation completed for MVC utilizes all of the previous characterizations.

The MEP Technical team members also include groundwater modeling staff from the U.S. Geological Survey (USGS). In the case of Martha's Vineyard, USGS modelers applied an existing, calibrated MODFLOW groundwater model of the Island originally developed by Whitman and Howard (1994) and updated by EarthTech, Inc. This existing model was used, together with the MODPATH USGS particle tracker, to delineate groundwater watersheds to Tisbury Great Pond. Based on the USGS output, Martha's Vineyard Commission staff and SMAST scientists reviewed and updated the Martha's Vineyard regional groundwater model. Regional watersheds were adopted by the MVC and are used in the MVC's guidance to the towns of the Martha's Vineyard and for the regulatory review of Developments of Regional Impact. MEP staff worked with Wilcox and other MVC staff to jointly re-review and refine the delineations in both the outwash and moraine portions of the Tisbury Great Pond watershed and subwatersheds, including the associated Black Point Pond subwatershed. Generally these reviews found that the Martha's Vineyard Commission watersheds are an adequate basis for MEP analysis..

III.2 TISBURY GREAT POND CONTRIBUTORY AREAS

The Tisbury Great Pond watershed and sub-watershed delineations are based on 1) water table contours measured in a few locations (*e.g.*, Wilcox, 1996) and modeled throughout the outwash plain and 2) USGS topographic maps in the western moraine. The modeled contours in the eastern portion of the watershed are based on MEP technical staff review of the subregional groundwater model originally prepared by Whitman Howard (1994) and subsequently updated by Earth Tech. This model organized much of the historic USGS geologic data collected on Martha's Vineyard and provided a satisfactory basis for incorporating the MEP refinements necessary to complete watershed delineation. The western portion of the watershed is in the less permeable western regional moraine and in this area the watershed and sub-watershed delineations are based on evaluation of topographic divides developed by MEP staff in consultation with MVC staff.

For the modeling portion of the watershed delineations, MEP technical staff revised the previously developed groundwater 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 previously for MassDEP-approved Zone II delineations for drinking water well contributing areas and the match was acceptable. This model was then used to define the portion of the watershed or contributing area to Tisbury Great Pond and its sub-estuaries within the model domain. This effort was coordinated with MVC and USGS staff. The Tisbury Great Pond watershed is situated in the central portion of Martha's Vineyard and is bounded by the Atlantic Ocean to the south (Figure III-1).

MEP staff utilized the Tisbury Great Pond watershed to develop daily discharge volumes for various sub-watersheds as calculated from the watershed areas and an island-specific recharge rate. In order to develop the groundwater discharge volumes, MEP and MVC staff determined an annual recharge rate of 28.7 inches for Martha's Vineyard. This recharge rate estimate is largely based on review of the relationship between recharge and precipitation rates used on Cape Cod, which has similar glacially derived aquifer soils. 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 average 44.5 in/yr of precipitation on the Cape. Precipitation data collected by the National Weather Service at Edgartown on Martha's Vineyard since 1947 has an average over the last 20 years of 46.9 in/yr (http://www.mass.gov/dcr/waterSupply/rainfall/precipdb.htm). If the Cape Cod relationship between precipitation and recharge is applied to the average Martha's Vineyard precipitation rate, the estimated recharge rate on Martha's Vineyard is 28.7 in/yr. This rate was used to estimate groundwater flow to the Tisbury Great Pond Embayment System and its various sub-watersheds (Table III-1). The sub-watershed discharge volumes were used to assist in the salinity calibration of the tidal hydrodynamic model. The overall estimated groundwater flow into Tisbury Great Pond from the MEP delineated watershed is 89,728 m3/d.

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

Watershed	Watershed #	Watershed Area (acres)	Discharge	
			m^3/day	ft^3/day
Middle Point Cove	1	330	2,668	94,223
Deep Bottom Cove	2	1,258	10,168	359,081
Tiah's Cove	3	879	7,106	250,945
Pear Tree Cove	4	1,187	9,593	338,769
Mill Brook	5	2,625	21,213	749,146
TGP Main	6	2,593	20,961	740,239
Tiasquam River	7	1,784	14,416	509,087
Black Point Pond	8	446	3,602	127,216
TOTAL		11,102	89,728	3,168,706

NOTE: Discharge rates are based on 28.7 inches per year of recharge, which is based on average precipitation recorded at Edgartown over the past 20 years by the National Weather Service.

The MEP watershed delineation is similar in both distribution and area to previous delineations. Woodruff and Sanders (1989) estimated a 11,679-acre watershed to Tisbury Great Pond based largely Delaney's (1980) water table map (Figure III-2). Wilcox (1996) estimated a 10,841-acre watershed by modifying the 1989 watershed using water table measurements from newly installed groundwater wells. A more recent delineation of just the Mill Brook watershed, which is based on the same data and includes Parsonage Pond, shows a sub-watershed area of 3,027 acres (ESS, 2012). Considerations of all of these results and results from adjacent watersheds (e.g., Howes, *et al*., 2007), and consultation with and refinements by MVC and USGS staff, MEP Technical Team Staff are highly confident that the delineation in Figure III-1 is accurate and an appropriate basis for completion of the linked watershed-embayment model for the Tisbury Great Pond Embayment System.

Since the tidal inlet between Tisbury Great Pond and the Atlantic Ocean periodically closes and the pond water level is topographically lower than the surrounding land, measurement of the water levels in the pond following a closure offer the opportunity to check the total watershed recharge into the pond. Dr. Kent Healy, as reported in Wilcox (1996) measured water levels during four opening/closing cycles during 1994 (Figure III-3). During these four cycles, which ranged from 31 to 114 days, the water level of the pond increased between 0.03 and 0.09 feet per day. Holding the measured surface area of the pond constant and discounting any increase in area due to the water level rise, the matching watershed inflow to the pond would range between 32,000 and 93,000 m3/d. Fugro-McClelland (1992) measured water levels in wells around the pond during a similar closure cycle and estimated a range of 18,927 m3/d to 56,781 m3/d. The variability in these flows is generally consistent with some of the variability measured in other water flow factors in this system (*e.g.*, streamflow). The MEP watershed delineation flows generally fit within these ranges, especially considering the likely variability in moraine infiltration and runoff. In addition, freshwater inflow determined from pond level rise during closured does not take into account seepage of pondwater out through the barrier beach, so the actual recharge rate should be higher than the increased pond volume.

In order to further evaluate the watershed delineations, MEP staff reviewed other collected information including Mill Brook and Tiasquam River flow data collected by Dr. Kent Healy, reviews of this data by Bill Wilcox of the MVC, historic groundwater levels, and data in other studies (*e.g.*, ESS, 2012). Dr. Kent Healy has collected streamflow data at Mill Brook and Tiasquam River since 1994. Review of this data has indicated a wide range of flow: 5,350 to 25,819 m3/d at Mill Brook and 3,132 to 15,116 m3/d at the Tiasquam River. Wilcox's review of the data yielded averages of 14,027 m3/d and 8,212 m3/d, respectively (personal communication, 2011). As detailed in Section IV.2, the measured MEP average flows during the 2006 water year (September 2005 through August 2006) were 17,363 m3/d for Mill Brook and 12,191 m3/d for the Tiasquam River. Estimated flows based on the MEP watershed area are higher than the averages, but less than the upper limit of the Healy ranges.

Although the MEP average flows easily fit within the Mill Brook and the Tiasquam River long term measured ranges, MEP staff reviewed other data to see if the comparisons to the long-term averages reported from Dr. Kent Healy's data were appropriate. The MVC measures a series of groundwater wells around the island on a monthly basis. Since groundwater levels will have an impact on flow in these groundwater fed streams, staff reviewed water level records from a wells (XEW39) located in West Tisbury that has been measured since November 1991. Review of groundwater levels at XEW39 indicates that water levels during the MEP streamflow measuring period were 7% above the average groundwater level during the well's period of record. If one reduced the MEP measured flows by 7%, the adjusted flows still fit within the overall range, but are closer to Healy's long-term averages.

Further discussion of the flows with Bill Wilcox of the MVC indicated that part of the difference in flow volumes might stem from how watershed flow moves around Mill Pond and where the gauges are located. The configuration of Mill Brook includes a diversion of a portion of its flow into Parsonage Pond, which is located near the southwest corner of Mill Pond, as well as other diversions south of Scotchman's Lane. Wilcox has estimated that 30% of the flow from Mill Brook into Mill Pond may be diverted. Inclusion of this factor in the Mill Brook flow would increase the Healy average to 18,324 m3/d and the range to 6,955 m3/d to 33,565 m3/d. The midpoint for the adjusted range is 20,260 m3/d or only 5% less than the MEP watershed flow. This finding reinforces that the measured flow data and the watershed discharge data are yielding comparable volumetric fluxes.

Review of the Tiasquam River sub-watershed brought forward additional evidence the MEP flows, based upon watershed water balance, are reasonable. Upstream of the location of the Tiasquam River MEP gauge are a series of small impoundments. Staff review of these impoundments based on the aerial maps available on Google Earth showed that their area fluctuated extensively during the period from 2005 to 2012; one pond of these ponds tripled in surface area between 2005 and 2009. This level of fluctuation is consistent with the high variability and large ranges measured by Healy in the Tiasquam River flow.

Review of watershed delineations for Tisbury Great Pond and its tributaries 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 delineation and freshwater discharge 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, such as would be the case in the area of the State Forest. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the aquatic systems within the overall watershed and ultimately to the estuarine waters of the Tisbury Great Pond system (Section V.1).

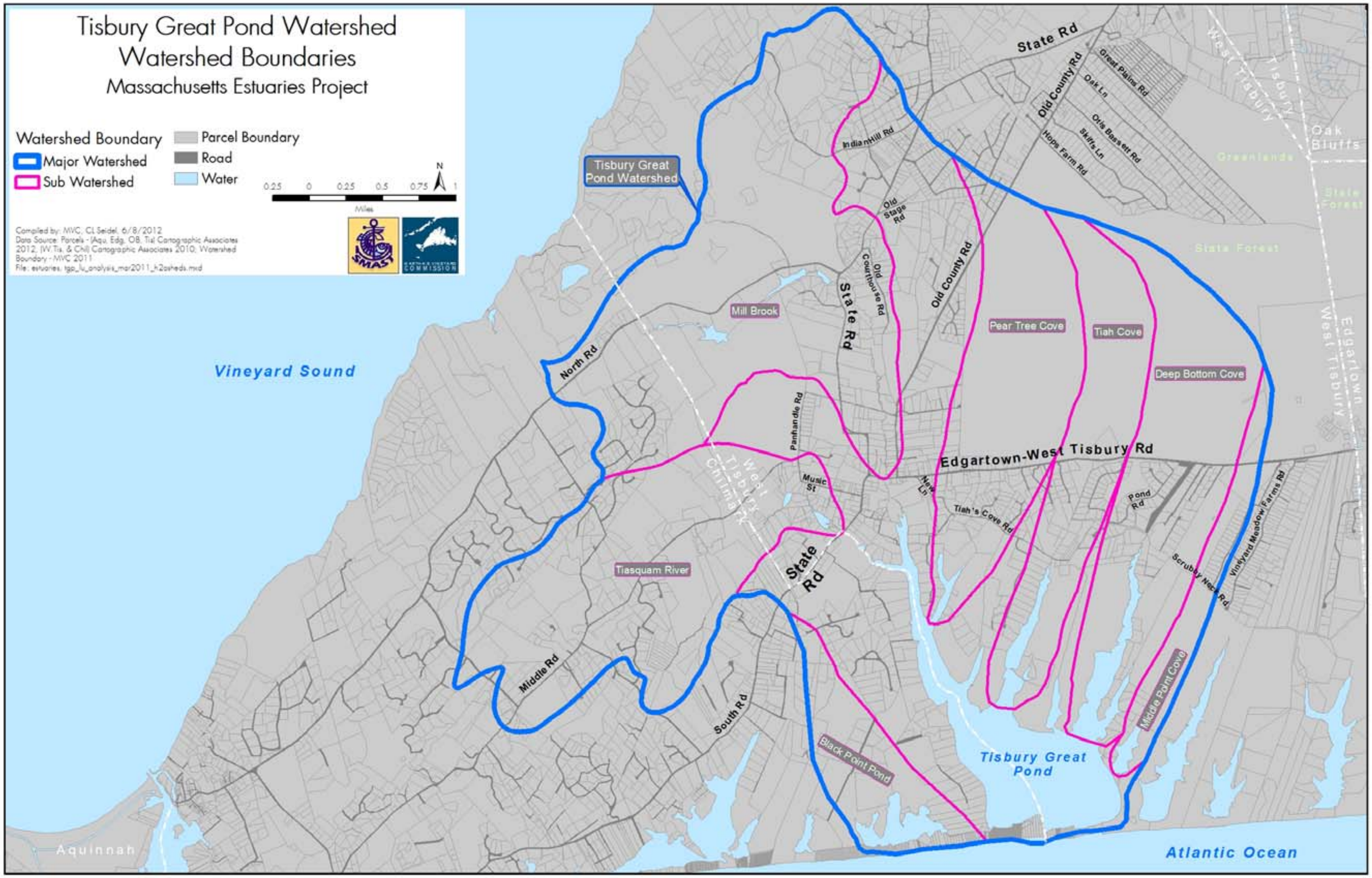

Figure III-1. Watershed and sub-watershed delineations for the Tisbury Great Pond Embayment System. Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI).

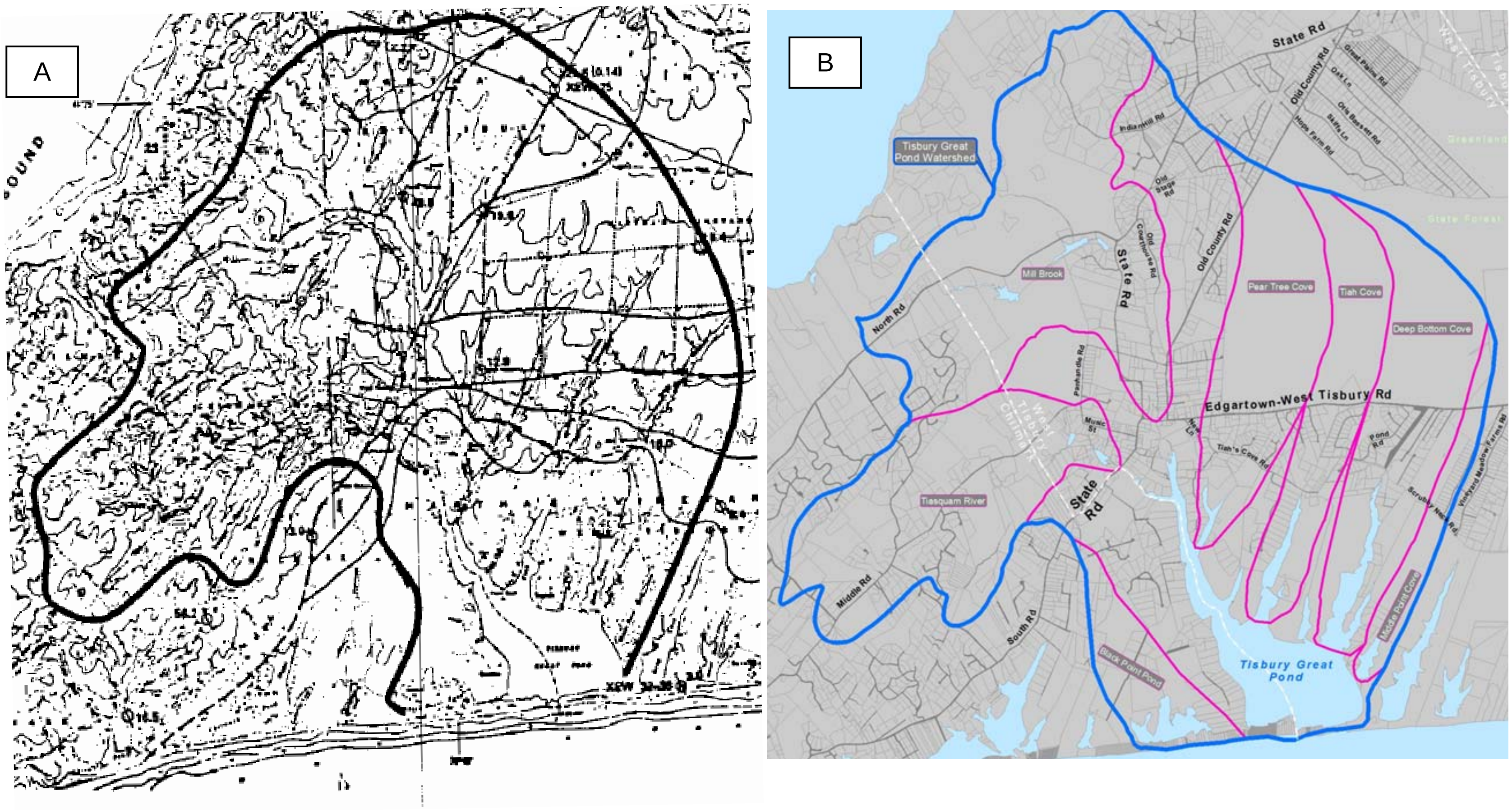

Figure III-2. Comparison of current MEP watershed delineation of the Tisbury Great Pond Embayment System (Panel B) and the previous delineation (Panel A) completed by Woodruff and Sanders (1989). The MEP watershed delineation, which reflects subsequent data collection, is 5% smaller than the 1989 delineation and includes sub-watershed delineations.

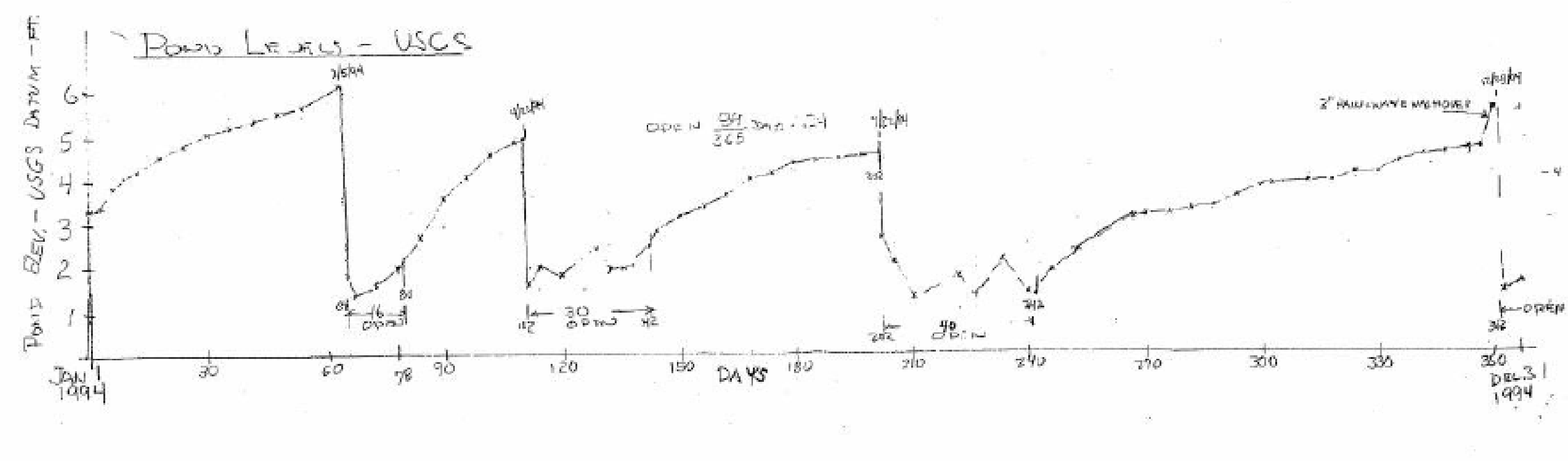

Figure III-3. Water level elevations in Tisbury Great Pond and the effect of 4 inlet openings in 1994 (modified from Figure 2 in Wilcox (1996), data collected by Dr. Kent Healy): March 5, April 22, July 22, and December 23. Water levels drop with the re-establishment of tidal exchange and then gradually increase as the opening closes and watershed freshwater discharges continue. Review of the water elevation time-series during the closed periods provides a reasonable check on watershed freshwater discharges to the estuary. Analysis of the four events show water level increases of between 0.03 and 0.09 ft/d during closure corresponding to watershed inflow volumes of between 32,000 and 93,000 m3/d. The MEP watershed freshwater discharge to the estuary based on watershed area and recharge is also within this range.

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

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

The MEP Technical Team coordinated the development of the watershed nitrogen loading for the Tisbury Great Pond Embayment System with Martha's Vineyard Commission (MVC) staff. This effort led to the development of nitrogen-loading rates (Section IV.1) to the Tisbury Great Pond Embayment System watershed (Section III). The watershed was sub-divided into eight (8) sub-watersheds, including Black Point Pond, to define contributing areas to each of the major embayment basins and to allow partitioning of nitrogen transport via groundwater and surface water streams discharging to the Tisbury Great Pond estuary.

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

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. Attenuation through the ponds is conservatively assumed to equal 50% unless available monitoring and pond physical data is reliable enough to calculate a pond-specific attenuation factor. Attenuation through streams is usually based on site-specific study of streamflow. In the Tisbury Great Pond Embayment System watershed, there are delineated watersheds to two streams (Mill Brook and Tiasquam River) and the only pond with a delineated watershed is Mill Pond, which is also the terminus and gauge location for Mill Brook. Surface water attenuation in Mill Brook and Tiasquam River is discussed in the stream section below (Section IV-2). Other, smaller aquatic features within the watershed to Tisbury Great Pond do not have separate watersheds delineated and, thus attenuation in these features are not explicitly included in the watershed analysis. If these small features were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (~5%) overestimated given the distribution of nitrogen sources, the locations of the gauges, and the locations of these features within the watershed.

Based upon the evaluation of the watershed and the various estimated sources of nitrogen, the MEP Technical Team used the Watershed Nitrogen Loading Sub-Model estimate of nitrogen loading for the sub-watersheds that directly discharge groundwater to the estuary without flowing through an interim pond or stream. Reductions in sub-watershed nitrogen loads were made to account for natural attenuation in ponds or streams. Internal nitrogen recycling was also determined throughout the tidal reaches of the Tisbury Great Pond Embayment 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 (2005), the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Martha's Vineyard Commission (MVC) staff, with the guidance of Estuaries Project staff, combined digital parcel and tax assessors' data from the MVC Geographic Information Systems Department. Digital parcels and land use/assessors data are from 2010. These land use databases contain traditional information regarding land use classifications (*e.g.*, MADOR, 2009) plus additional information developed by the MVC.

Figure IV-1 shows the land uses within the Tisbury Great Pond Estuary watershed area. Land uses in the study area are grouped into eight land use categories: 1) residential, 2) commercial, 3) mixed use, 4) industrial, 5) agricultural, 6) undeveloped (including residential open space), 7) public service/government, including road rights-of-way, and 8) freshwater (e.g., ponds). These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2009). "Public service" in the MADOR system is tax-exempt properties, including lands owned by town or state government (*e.g.*, open space, roads, state forest) and private groups like churches and colleges.

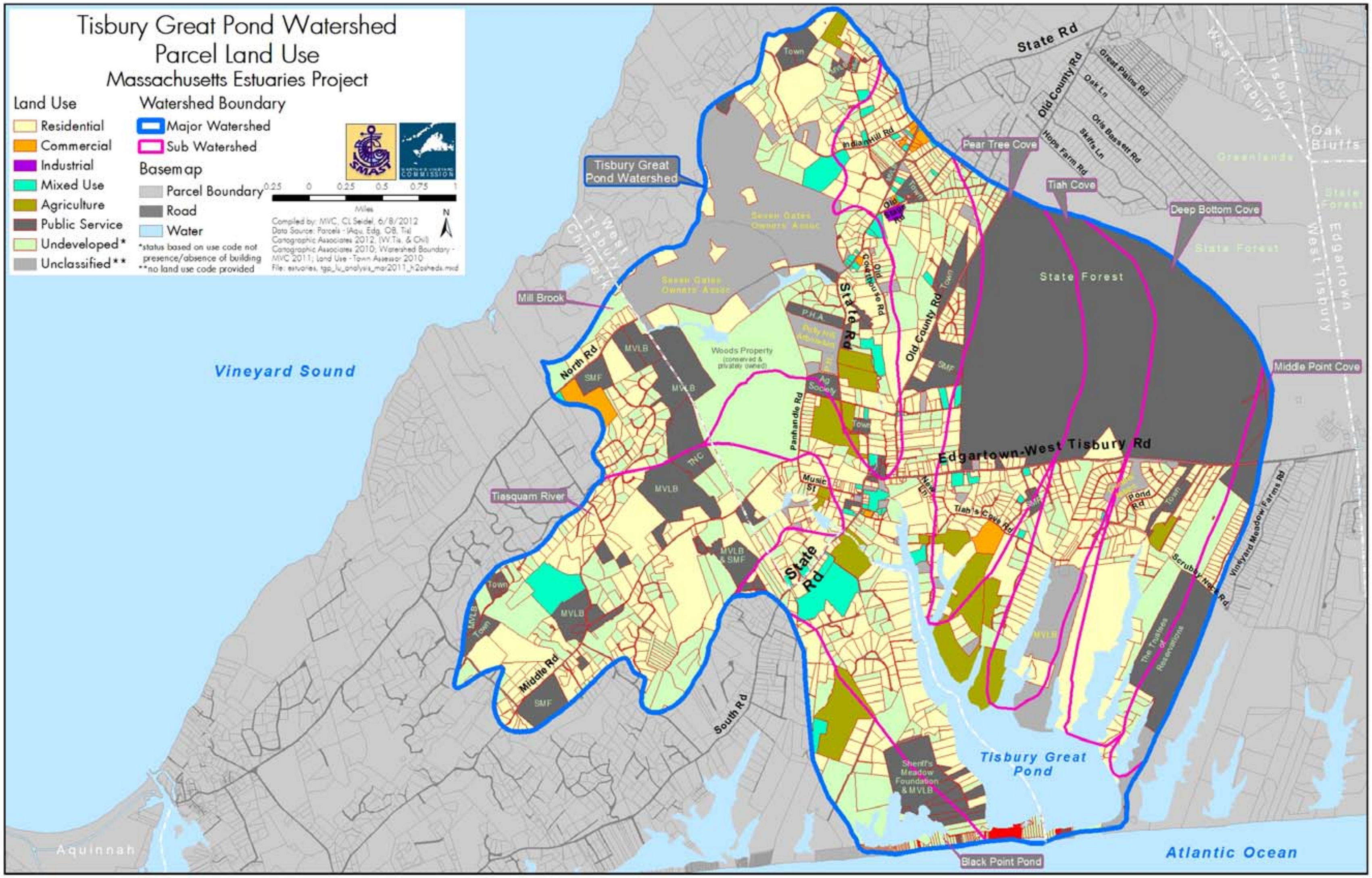

Figure IV-1. Land-use in the Tisbury Great Pond Embayment System watershed. The watershed extends over portions of two towns: West Tisbury and Chilmark. Land use classifications are based on assessors' records provided by each of the towns.

In the overall Tisbury Great Pond System watershed, the predominant land use based on area is residential parcels, which accounts for 37% of the overall watershed area; public services/rights-of-way are the second highest percentage of the system watershed (33%) (Figure IV-2). Single-family residences (MADOR land use code 101) are 62% of the overall system residential land area. Public service land uses are the dominant land use category in the four eastern sub-watersheds, largely due to the state forest. Residential land uses are the dominant land use category in the Mill Brook, Tiasquam River, and Tisbury Great Pond main basin sub-watersheds, as well as the overall system watershed. Undeveloped land is the predominant land use in the Black Point Pond sub-watershed (39%). Undeveloped parcels are generally the third highest land use area classification in each of the sub-watersheds. Overall, undeveloped land uses account for 24% of the entire Tisbury Great Pond watershed area.

In all the sub-watershed groupings shown in Figure IV-2, residential parcels are the dominant parcel type except in the sub-watershed to Black Point Pond, generally ranging between 55% and 79% of all parcels in these sub-watersheds. Residential parcels are only 21% of the parcels in the Black Point Pond sub-watershed, where 70% of the parcels are classified as undeveloped. Overall, 59% of all parcels in the whole Tisbury Great Pond Embayment System watershed are classified as residential. Single-family residences (MassDOR land use code 101) are 72% to 92% of residential parcels in the individual sub-watersheds and 79% of the residential parcels throughout the whole Tisbury Great Pond System watershed.

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

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

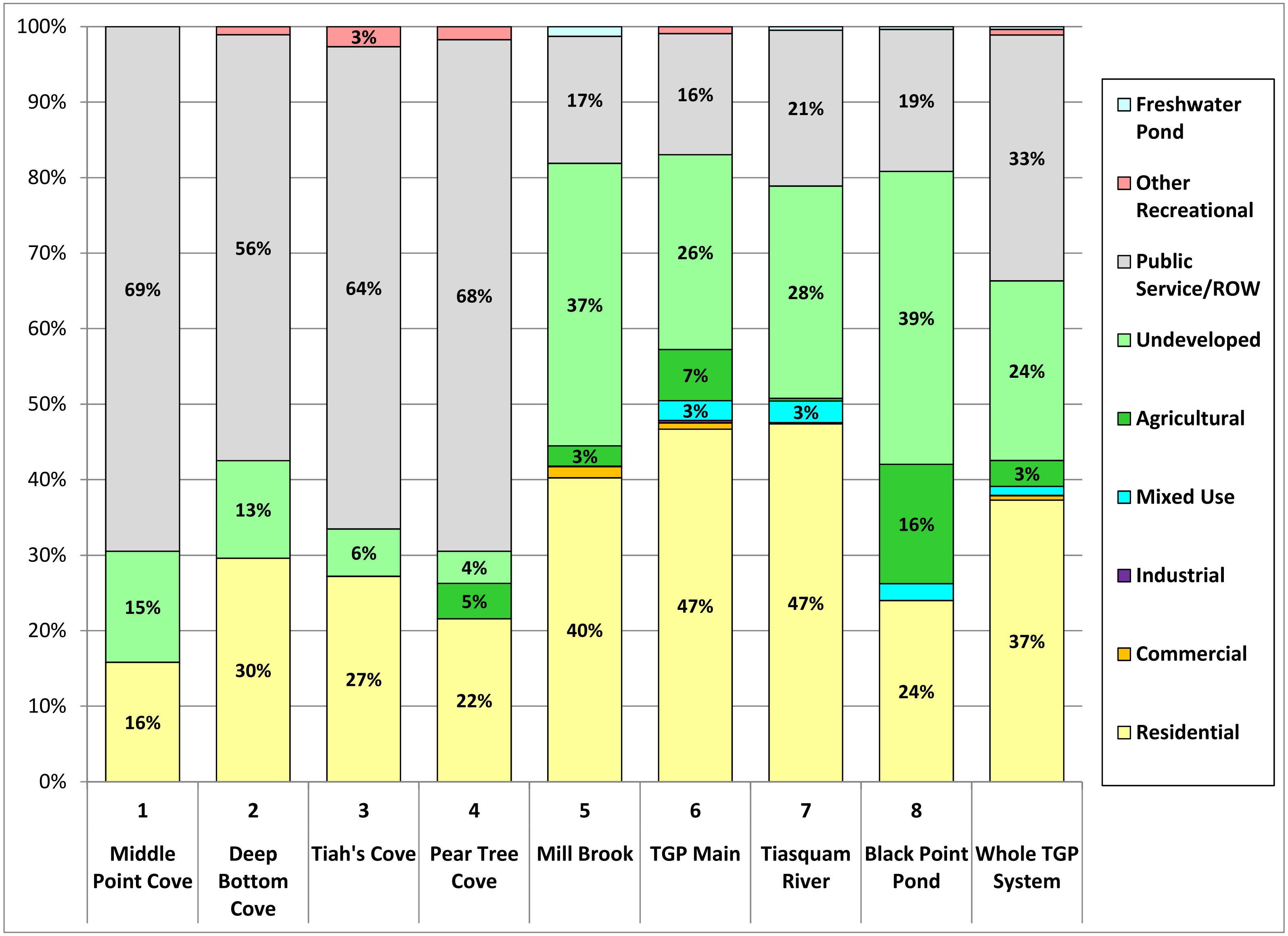

Figure IV-2. Distribution of land-uses within the sub-watersheds and whole watershed to Tisbury Great Pond. Only percentages greater than or equal to 3% are shown. Land use categories are based on town and Massachusetts DOR (2009) classifications.

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

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

The nitrogen loads developed using this approach have been validated in a number of long and short-term field studies where integrated measurements of nitrogen discharge from watersheds could be directly measured. Weiskel and Howes (1991, 1992) conducted a detailed watershed/stream tube study that monitored septic systems, leaching fields and the transport of the nitrogen in groundwater to adjacent Buttermilk Bay. This monitoring resulted in estimated annual per capita nitrogen loads of 2.17 kg (as published) to 2.04 kg (if new attenuation information is included). Modeled and measured nitrogen loads were determined for a small sub-watershed to Mashapaquit Creek in West Falmouth Harbor (Smith and Howes, manuscript in review) where measured nitrogen discharge from the aquifer was within 5% of the modeled N load. Another evaluation was conducted by surveying nitrogen discharge to the Mashpee River in reaches with swept sand channels and in winter when nitrogen attenuation is minimal. The modeled and observed loads showed a difference of less than 8%, easily attributable to the low rate of attenuation expected at that time of year in this type of ecological situation (Samimy and Howes, unpublished data).

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

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

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

In order to estimate wastewater flows, MEP staff generally work with municipal or water supplier partners in the study watershed to obtain parcel-by-parcel water use information. However, in the Tisbury Great Pond watershed, private wells supply much of the drinking water. With this in mind, MVC staff contacted the Tisbury Water Works and obtained four years (2002-2005) of water use information. Average water uses for various land use categories were developed from this data and assigned to properties classified in the same land use categories in the Tisbury Great Pond watershed. Review of the water use dataset found that single family residences (MADOR land use code 101) averaged 160 gallons per day (gpd), two family residences (MADOR land use code 104) averaged 249 gpd, three family residences (MADOR land use code 105) averaged 315 gpd, and multiple houses on one parcel (MADOR land use code 109) averaged 255 gpd. Average water use was also determined for a variety of other non-residential land uses and site-specific flows were developed based on review of the parcels (*e.g.*, a parcel classified as a MADOR land use code 718, pasture land use was assigned the two family water use based on having two houses on the property). These average water uses were used to determine individual parcel water uses in the Tisbury Great Pond watershed. Water use is used as a proxy for wastewater generation from septic systems on all developed properties in the watershed. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the average water-use, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2).

In order to provide an independent validation of the average residential water use within the Tisbury Great Pond Embayment System watershed, MEP staff reviewed US Census population values for the Towns of West Tisbury and Chilmark. 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 2010 US Census, average occupancy within West Tisbury and Chilmark is 2.29 and 2.18 people per occupied housing unit, respectively. Year-round occupancy of available housing units is 56% and 27% for West Tisbury and Chilmark, respectively. These rates are down slightly from the 2000 US Census. Housing units classified as seasonal increased slightly between the two Censuses. Based on the 2010 average occupancy rate, the average water use, employing the per capita Title 5 water use value, is 126 gpd for West Tisbury and 120 gpd for Chilmark.

Given that such a high percentage of housing units on Martha's Vineyard are occupied only on a seasonal basis, estimates of water use based on Census data should include seasonal population increase. Estimates of summer populations on Cape Cod and the Islands derived from a number of approaches (*e.g.*, traffic counts, garbage generation, WWTF flows) generally suggest average summer population increases from two to three times the year-round residential populations measured by the US Census. If it is conservatively assumed that seasonally-classified residential properties in West Tisbury and Chilmark are occupied at twice the year-round occupancy for three months, the estimated average town-wide water uses would be 157 and 150 gpd, respectively. Given that the average water use for single family residences on metered water supply in the Tisbury Great Pond watershed is 160 gpd, this analysis of Census data indicates that the average water use is reasonably reflective of population estimates.

Commercial and industrial properties were largely treated the same as residential properties, *i.e.* use of measured water use for similar land use classifications. There are 32 commercial properties in the Tisbury Great Pond watershed (1% of the total parcels) and three (3) classified as industrial properties. Most of these properties are located in the Tisbury Great Pond Main Basin sub-watershed (sub-watershed #7).

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, cranberry bogs and other agricultural land uses, and golf courses, 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 Tisbury Great Pond Embayment System, MVC staff under the guidance of MEP technical team reviewed available information about residential lawn fertilizing practices and agricultural fertilizer usage. There are no golf courses or cranberry bogs within the Tisbury Great Pond 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 unless site-specific or watershed-specific data is available.

In order to complete the Tisbury Great Pond watershed nitrogen loading, MVC staff assisted the MEP technical team by measuring the lawn areas of approximately 200 parcels grouped in selected areas of the watershed (W. Wilcox, personal communication). This review found that residential lawn areas averaged approximately 9,600 square feet in the eastern portion of the watershed and 6,100 square feet in other portions of the watershed. These areas were applied on a sub-watershed basis with sub-watersheds 1-4 assigned the higher area value. MVC staff also determined individual lawn size on selected larger parcels based on review of aerial photographs; these site-specific areas were also included in the watershed loading model. MVC staff also determined sub-watershed-specific nitrogen fertilizer application rates based on a previous survey of lawn conditions. Other factors in the model are those generally used in MEP nitrogen loading calculations.

Nitrogen Loading Input Factors: Agricultural Areas

Working with MEP staff, MVC staff also reviewed all parcels classified as agricultural (MADOR land use codes 700s), as well as farms on other non-farm coded properties, and determined the area of fertilized crops. Nitrogen application rates and leaching rates are based on standard MEP agricultural crop loading factors that have been developed for use in other MEP analyses on Martha's Vineyard. According to this review, the watershed has over 550 acres of cropland and while most of the nitrogen is cycled within the cropland, the fraction that reaches the estuarine waters of the Tisbury Great Pond Embayment System accounts for 2,642 kg N/yr of the total watershed nitrogen load.

MVC staff also identified the number of farm animals within the watershed. This analysis counted 406 animals total, with sheep (36%) and chickens (22%) being the most common. MEP nitrogen loading factors have previously been developed for farm animals, including nitrogen leaching rates, and species-specific total nitrogen releases were applied. According to this review, these animals add 2,895 kg/yr of nitrogen to the Tisbury Great Pond watershed.

Nitrogen Loading Input Factors: Landfills

The West Tisbury and Chilmark landfills are both located within the Tisbury Great Pond watershed; the West Tisbury landfill is located in the Main Basin sub-watershed (#6), while the Chilmark landfill is located within the Tiasquam River sub-watershed (#7). According to MassDEP databases, the Chilmark landfill was capped in 2004, while the West Tisbury landfill was capped in 1997. MVC staff obtained groundwater monitoring data from two periods (1989-92 and 2005-10) for both landfills. MEP staff determined the area of solid waste disposal from a review of aerial photographs and use of GIS techniques and reviewed the groundwater monitoring data to determine residual nitrogen loads from each landfill.

In order to assess nitrogen loading from a landfill, groundwater monitoring wells must be placed along reliable groundwater flow paths and screened at appropriate depths, as well as having samples from the wells be analyzed to capture all nitrogen forms since groundwater plumes from capped landfills are initially anaerobic and usually begin to oxidize with time resulting in a shift in dominant nitrogen form (ammonium to nitrate). The available groundwater monitoring data for the landfills in this watershed are fairly extensive during the 1989-1992 period, but later sampling did not include all the available wells or consistently include ammonium-nitrogen or other measures that would include non-oxidized forms of nitrogen. For these reasons, the landfill loads rely extensively on earlier data, which means that the nitrogen loads from the landfills are likely somewhat conservative, as the contribution from the landfill has almost certainly been diminishing over time since the cap was emplaced.

Based on the available data, MEP staff determined that the net nitrogen concentration discharging from the West Tisbury landfill is 0.77 mg/l, while the net nitrogen concentration discharging from the Chilmark landfill is 3.49 mg/l. Net concentrations are averages of down-gradient well concentrations minus averages of upgradient well concentrations. Using the landfill areas and the assigned watershed recharge rate, MEP staff estimated an annual nitrogen load of 13 kg/yr from the West Tisbury landfill and 89 kg/yr from the Chilmark landfill. These loads are included in the watershed nitrogen loading for the Tisbury Great Pond Embayment System.

Nitrogen Loading Input Factors: Other

One of the other key factors in the nitrogen loading calculations is recharge rates associated with impervious surfaces and natural areas. As discussed in Section III, Martha's Vineyard-specific recharge rates were developed and utilized based on comparison to the precipitation data in Edgartown and results of the USGS groundwater modeling effort in areas of similar post-glacial aquifer soils 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 Tisbury Great Pond watershed are summarized in Table IV-1.

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 assignment 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. 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 Tisbury Great 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.

Table IV-1. Primary Nitrogen Loading Factors used in the Tisbury Great Pond MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from watershed-specific data.

Nitrogen Concentrations:	mg/l	**Recharge Rates:**[2]	in/yr
Road Run-off	1.5	Impervious Surfaces	42.2
Roof Run-off	0.75	Natural and Lawn Areas	28.7
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:[3]	
Natural Area Recharge	0.072	Existing and buildout single family residences (land use code 101)	160 gpd
Wastewater Coefficient	23.63		
Town of West Tisbury Landfill Load (kg/yr)	13	Two-family residential (land use code 104)	249 gpd
Town of Chilmark Landfill Load (kg/yr)	89	Three-family residential (land use code 105)	315 gpd
Fertilizers:		Multiple houses on same lot residential (land use code 109)	255 gpd
Average Residential Lawn Size (sq ft)[1]	6,100/ 9,600	Other sites water used generally based on averages of same land use classifications occasionally modified based on MVC staff knowledge.	
Residential Watershed Nitrogen Rate (lbs/1,000 sq ft)[1]	1.7/ 1.1	Commercial Buildout additions	
Nitrogen leaching rate	20%	Wastewater flow (gpd/1,000 ft2 of building):	48.4
Average Single Family Residence Building Size (based on bldg areas; sq ft)	1,850	Building coverage:	18%
Farm Animals	kg/yr /animal	**Crops**[4]	kg/ac/yr
Horse	32.4	Hay, Pasture	18
Cow/Steer	55.8	Row Crop/Nursery	55
Sheep	7.3	Crop N leaching rate	%
Hogs/Pigs	14.5	Hay, Pasture	25%
Chickens	0.4	Row Crop/Nursery	33%
Animal N leaching rate	40%	Greenhouse	10%

1) MVC staff measured a sample of lawns in different portions of the watershed and found that lawns in the eastern portion averaged 9,600 square feet, while other portions averaged 6,100 square feet. MVC also completed a lawn survey and determined watershed-specific N applications rates for the two portions.
2) Based on precipitation rate of 46.9 inches per year (20 year average at long-term Edgartown station); recharge is based on recharge to precipitation relationship used in Cape Cod groundwater modeling (Walter and Whealan, 2005).
3) All developed parcels in the watershed utilize private wells; water use estimates are based on averages for same land use classifications based on four years (2002-2005) of water use from Tisbury Water Works. The values represent total water-use per land-use type.
4) Crop loading rates & leaching rates are based on local knowledge developed by MVC staff.

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 Tisbury Great Pond Embayment System Watershed Nitrogen Loading module with summaries for each of the individual sub-watersheds. The sub-watersheds generally are paired with functional embayment/estuary basins for the Linked Watershed-Embayment Model's water quality component.

For management purposes, the aggregated embayment watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Tisbury Great Pond System, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), the West Tisbury and Chilmark landfills, fertilizer (including residential lawns and agricultural sources), animal husbandry, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the watershed nitrogen-loading module is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-3). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model. Natural nitrogen attenuation in the Tisbury Great Pond watershed occurs to nitrogen that passes through Mill Pond/Mill Brook and the Tiasquam River.

Freshwater Pond Nitrogen Loads

Freshwater ponds on Cape Cod, Martha's Vineyard, and Nantucket are generally kettle hole depressions of the land surface that intercept the groundwater table within the aquifer providing what some call "windows on the aquifer." Kettle ponds are flow through systems, with groundwater typically flowing in along the up-gradient shoreline, then lake water flows back into the groundwater system along the down-gradient shoreline. Occasionally these ponds will also have a stream outlet or herring run that also acts as a discharge point. Since the nitrogen loads usually flow into a pond with the groundwater, it enters the nitrogen cycle of the pond ecosystems, which incorporate some of the nitrogen, retain some nitrogen in the sediments, and transform nitrogen among its various oxidized and reduced forms. As result of these interactions, some of the nitrogen never makes it to the down-gradient estuary, as it is removed through burial in the pond sediments or is denitrified and returns to the atmosphere. Following these reductions, the remaining (attenuated) loads flow back into the groundwater system along the down-gradient side of the pond or through a stream outlet and eventually discharge into the down-gradient embayment. The nitrogen load summary in Table IV-3 includes both the unattenuated (nitrogen load to each sub-watershed) and attenuated nitrogen loads to Mill Pond, the only freshwater pond in the Tisbury Great Pond watershed with a delineated watershed.

Table IV-2. Tisbury Great Pond Embayment System Watershed Nitrogen Loads. Present nitrogen loads are based on current land-uses and nitrogen associated activities, including fertilizer loads from golf courses and farms and residual loads from the West Tisbury and Chilmark capped landfills. Build-out loads include septic wastewater disposal, fertilizer, and impervious surface additions from developable properties. All values are kg N yr^{-1}.

		Tisbury Great Pond N Loads by Input (kg/yr):								Present N Loads			Buildout N Loads		
Watershed Name	Watershed ID#	Wastewater	Landfill	Fertilizers	Impervious Surfaces	Agriculture	Water Body Surface Area	"Natural" Surfaces	Buildout	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Tisbury Great Pond Total		6,053	102	1,200	1,030	6,508	4,551	2,147	2,723	21,592		21,319	24,315		23,979
Middle Point Cove	1	161	-	43	21	-	-	68	116	293	0%	293	409	0%	409
Deep Bottom Cove	2	450	-	121	95	78	24	255	654	1,023	0%	1,023	1,678	0%	1,678
Tiah's Cove	3	415	-	108	53	64	-	179	108	820	0%	820	927	0%	927
Pear Tree Cove	4	620	-	147	93	304	-	235	39	1,400	0%	1,400	1,439	0%	1,439
Mill Brook	5	840	-	78	184	1,522	203	495	289	3,321	5%	3,155	3,610	5%	3,430
TGP Main	6	2,339	13	575	403	4,269	-	466	295	8,065	0%	8,065	8,359	0%	8,359
Tiasquam River	7	1,066	89	112	162	272	79	355	972	2,135	5%	2,028	3,107	5%	2,951
Black Point Pond	8	163	-	16	20	-	-	93	250	292	0%	292	541	0%	541
Middle Point Estuary Surface	1						121			121	0%	121	121	0%	121
Deep Bottom Estuary Surface	2						550			550	0%	550	550	0%	550
Tiah's Cove Estuary Surface	3						283			283	0%	283	283	0%	283
Pear Tree Cove Estuary Surface	4						94			94	0%	94	94	0%	94
TGP Main Estuary Surface	6						2,858			2,858	0%	2,858	2,858	0%	2,858
Black Point Pond Estuary Surface	8						338			338	0%	338	338	0%	338

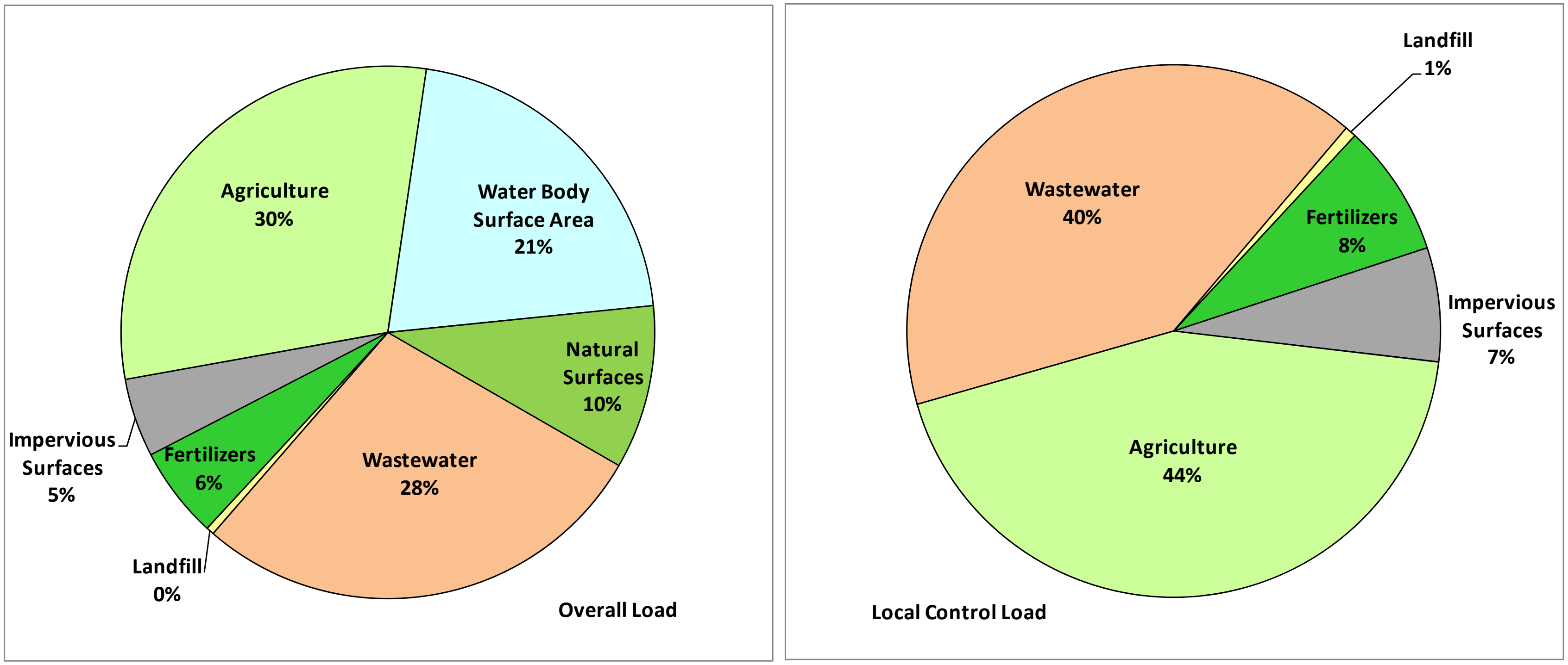

Figure IV-3. Unattenuated nitrogen load (by percent) for land use categories within the overall Tisbury Great Pond Embayment System watershed. "Overall Load" is the total nitrogen input to the watershed and estuary from all sources, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control (e.g. excludes atmospheric deposition and natural areas).

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

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

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

Within the Tisbury Great Pond watershed, Mill Pond is the only major freshwater pond and as such its watershed was delineated. Mill Pond has a recently completed bathymetric map (ESS, 2012) that shows its total volume as 5,275 cubic meters with an average depth of 0.5 meters. This pond volume is 1% greater than the pond volume determined based on an earlier bathymetry completed in 2006 (ACT, 2006). As mentioned in Section III, flow from the primary outlet from Mill Pond has been measured frequently, but has a wide range of discharge volumes. MVC staff review of Dr. Kent Healy’s measurements since 1994 show a range of 5,350 to 25,819 m3/d (Bill Wilcox, personal communication), while MEP flow measured at same location resulted in an average of 17,363 m3/d (see Section IV.2). The MEP watershed to the gauge location with a standard recharge rate results in a sub-watershed flow of 21,213 m3/d. Using the range established by Healy and the bathymetry by ESS, the residence time of water in Mill Pond is 0.2 to 1.0 days, while the MEP gauge flow yields 0.30 days and the MEP watershed recharge, 0.25 days. It is clear the MEP analysis fits well within the range of the long term record.

Short residence times offer little opportunity for natural nitrogen removal (or attenuation) in wetland, pond, or river systems (*e.g.*, Saunders and Kalff, 2001). Measurements collected in Mill Pond at the terminus of the Marstons Mills River in Barnstable, MA showed a nitrogen removal of 30% (Howes, *et al*., 2006), while Mill Pond in Yarmouth, MA showed a nitrogen removal of 8% (Howes, et al., 2007). The conservative nitrogen attenuation rate of 5% assigned to Mill Pond for Tisbury Great Pond is based on the available measurements (see Section IV.2) and is reasonably consistent with other similarly structured systems throughout the MEP study area.

Build-out

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

The build-out procedure used in this watershed and generally completed by MEP staff is to evaluate town zoning to determine minimum lot sizes in each of the zoning districts, including overlay districts (*e.g.*, water resource protection districts). Larger lots are subdivided by the minimum lot size to determine the total number of new lots. In addition, existing developed properties are reviewed for any additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence are assumed to have one additional residence at build-out. Most of the focus of new development is for properties classified as developable by the local assessor (state class land use codes 130 and 131 for residential properties). Properties classified by the town assessors as "undevelopable" (*e.g.*, codes 132 and 392) were not assigned any development at build-out. Commercial and industrial developable properties were not subdivided; the area of each parcel and the factors in Table IV-1 were used to determine a wastewater flow for these properties. Project staff typically reviews these initial results with local experts, who were MVC staff in this case, to produce a final MEP build-out assessment.

The build-out assessment completed for this review indicated that there are 689 potential additional residential dwellings and 172 potential additional guesthouse additions within the Tisbury Great Pond Embayment watershed. There are also 8.4 acres of potential additional commercial developable land. There is no additional industrial developable land. All parcels included in the build-out assessment of the Tisbury Great Pond Embayment System watershed are shown in Figure IV-4.

Nitrogen loads were developed for each of the build-out additions based largely on existing development factors within the Tisbury Great Pond Embayment System watershed. Additional build-out single-family residential dwellings were assigned a total water use flow of 160 gpd, which is based on the average water use for similar dwellings currently present within the watershed. The water use database was also used to determine average water use for commercial properties; existing properties have an average water use of 48.4 gpd/1,000 sq ft of commercial building. Review of building areas also found that commercial buildings occupy an average of 18% of each commercial parcel. Other factors used in the MEP build-out assessment are listed in Table IV-1. Table IV-2 presents a sum of the additional nitrogen loads by sub-watershed for the MEP build-out scenario. This sum includes the wastewater, fertilizer, and impervious surface loads from additional residential dwellings added, as well as loads from projected guesthouse and commercial build-out additions. Overall, the whole of the Tisbury Great Pond Embayment System watershed is presently near build-out and when fully developed the total unattenuated nitrogen loading to the watershed will increase by only 13%.

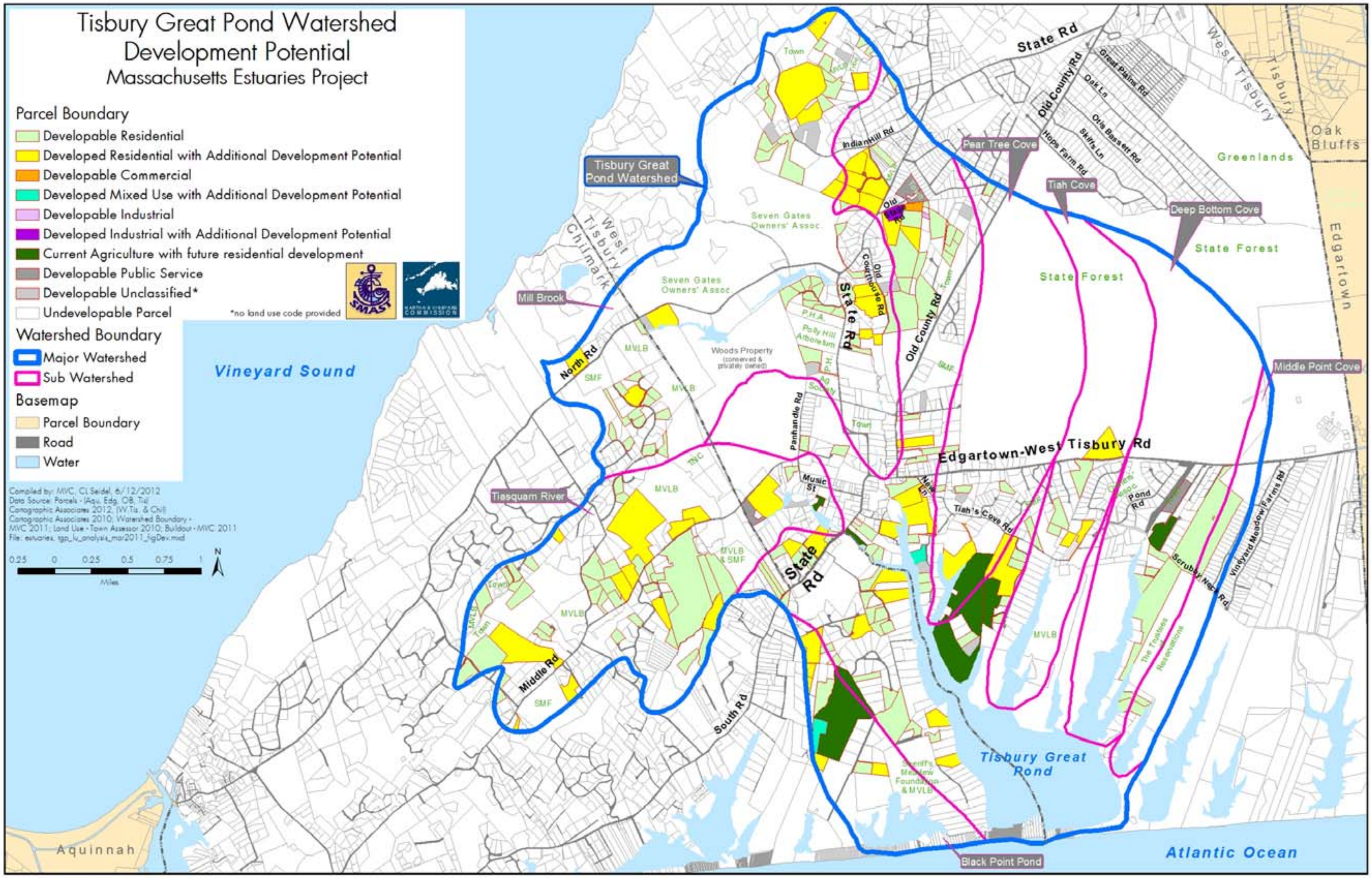

Figure IV-4. Developable Parcels in the Tisbury Great Pond Embayment System watershed. Developable parcels and developed parcels with additional development potential are highlighted. Nitrogen loads in the build-out scenario are based on additional development assigned to these parcels.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

IV.2.1 Background and Purpose

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out, sewering analysis, enhanced flushing, pond/wetland restoration for natural attenuation, etc.) to changes in water quality and habitat health within the receiving estuary. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the sub-watersheds of the Tisbury Great Pond Embayment System being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1).

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

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

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP Approach in the Tisbury Great Pond Embayment System. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the estuary in addition to the natural attenuation measures by fresh kettle ponds in the overall watershed, addressed above (Section IV.1). These additional site-specific studies were conducted in the 2 major surface water flow systems in the Tisbury Great Pond System watershed, 1) Mill Brook discharging to the head of Town Cove (main tributary sub-basin) of the Tisbury Great Pond system and 2) Tiasquam River, a relatively large stream also discharging to Town Cove (head of the Tisbury Great Pond system). Additionally, the results of these site specific studies on Mill Brook and the Tiasquam River were reconciled against historic flow measurements conducted during the 1990’s and 2000’s (K. Healy) as a check for consistency. Together these 2 streams "drain" the recharge and transport the recharge from 2 sub-watersheds that combined account for ~40% of the total watershed area to the estuary.

Quantification of watershed based nitrogen attenuation is contingent upon being able to compare nitrogen load to the embayment system directly measured in freshwater stream flow (or in tidal marshes, net tidal outflow) to nitrogen load as derived from the detailed land use analysis (Section IV.1). Measurement of the flow and nutrient load associated with the freshwater streams discharging to the estuary provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up-gradient from the gauging sites. Flow and nitrogen load were measured at the gauges in each freshwater stream site for approximately 17 months of record depending on the stream gauging location (Figure IV-5). For each time-series period, velocity profiles were completed on each river every month to two months. The summation of the products of stream subsection areas of the stream cross-section and the respective measured velocities represent the computation of instantaneous stream flow (Q).

Determination of stream flow at each gauge was calculated and based on the measured values obtained for stream cross sectional area and velocity. Stream discharge was represented by the summation of individual discharge calculations for each stream subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire stream cross section were averaged and then applied to the total stream cross sectional area.

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

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

where by:

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

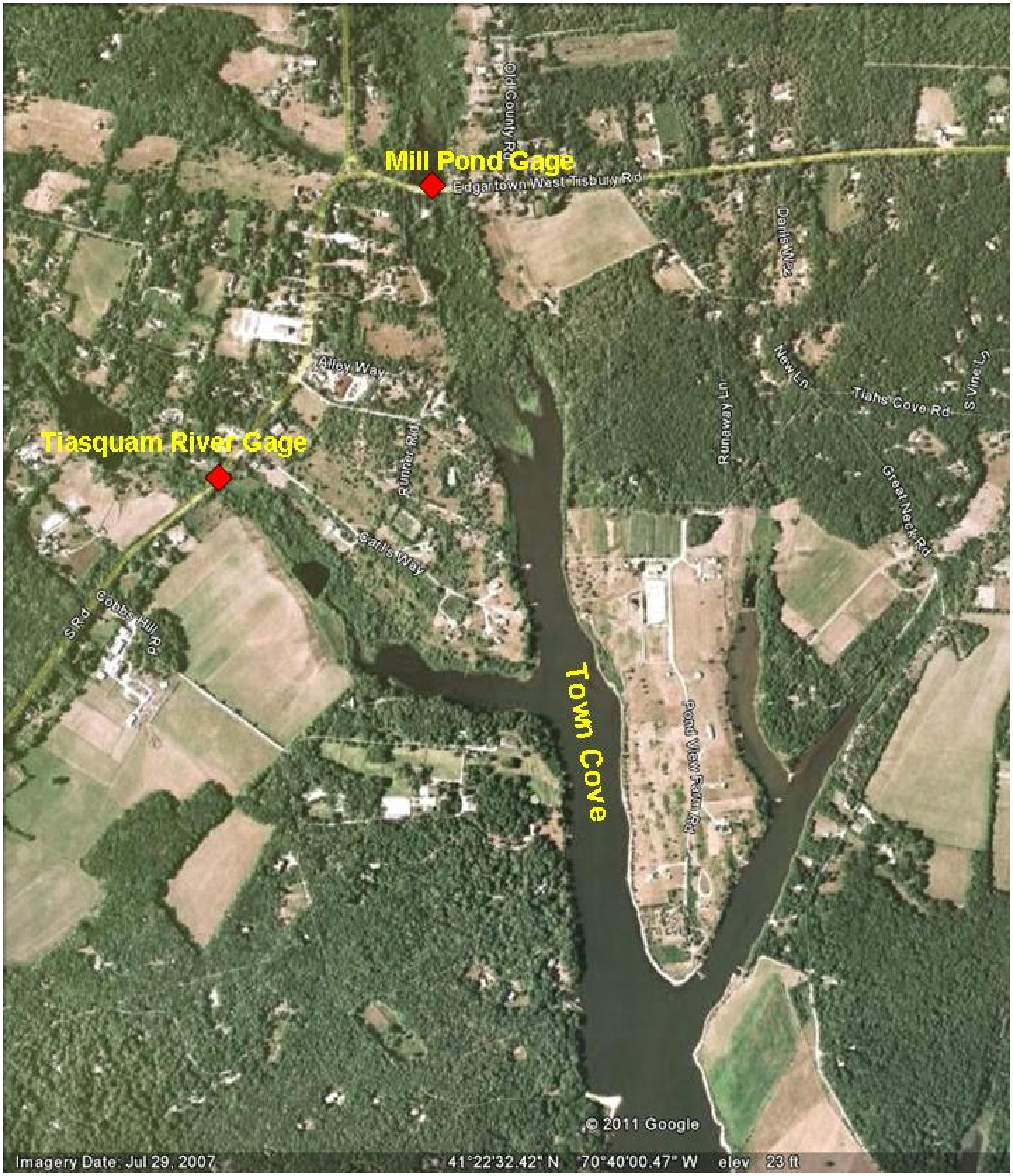

Figure IV-5. Location of Stream gauges (red diamonds) in the Tisbury Great Pond Embayment System watershed. The combined sub-watershed areas contributing to the gauge sites covers ~40% of the entire watershed to the estuary.

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

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

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

IV.2.2 Surface Water Discharge and Attenuation of Watershed Nitrogen: Mill Brook

Mill Pond, located immediately up gradient of the Mill Brook gauge site (Edgartown-West Tisbury Road crossing) is a small freshwater pond and unlike many of the freshwater ponds on Martha's Vineyard and Cape Cod, this pond has stream outflow rather than discharging solely to the aquifer along its down-gradient shore. Since Mill Pond is relatively small and shallow, it has a rapid water turnover time (<1 day). This stream outflow, Mill Brook and the Pond's rapid turnover, likely serves to decrease the pond's attenuation of nitrogen, however, the stream outflow provides for a direct measurement of the sub-watershed nitrogen load to the estuary and the level of nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands, small impoundments and streambed associated with Mill Brook. The combined rate of nitrogen attenuation by all of these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to Mill Brook above the gauge site and the measured annual discharge of nitrogen to the tidal portion (when the pond is breached) of the Town Cove portion of the Tisbury Great Pond System, Figure IV-5.

At the Mill Brook gauge site, a continuously recording vented calibrated water level gauge was installed to yield the level of water in the lower reach of Mill Brook. As the Town Cove portion of the Tisbury Great Pond Embayment System is tidally influenced when the pond is periodically breached, the gauge was located as far down gradient along Mill Brook such that a complete measure of attenuation in the sub-watershed could be obtained and also such that freshwater flow could be measured at low tide during breach events and at high stand when the pond was closed. To confirm that freshwater was being measured, the stage record was analyzed for any tidal influence during the deployment period and salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average salinity during the entire deployment period was determined to be 0.1 ppt. Therefore, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked monthly. The gauge on Mill Brook was installed on June 20, 2005 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued until November 9, 2006 for a total deployment of 17 months.

Surface freshwater flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Mill Brook site based upon these flow measurements and measured water levels at the gauge site. The rating curve was then used to convert the continuously measured stage data to obtain the daily volume of freshwater flow. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge to the head of the Town Cove portion of the Tisbury Great Pond System, immediately south of the Edgartown-West Tisbury Road bridge crossing, and reflective of the biological processes occurring in the stream channel and the small up-gradient impoundment of Mill Pond which contributes to nitrogen attenuation (Figure IV-6 and Table IV-3 and IV-4). In addition, a water balance was constructed based upon the U.S. Geological Survey confirmed groundwater flow model to determine long-term average freshwater discharge expected at each gauge site.

The annual freshwater flow record for Mill Brook measured by the MEP was compared to the long-term average flows determined by the groundwater modeling effort (Table III-1). The measured freshwater discharge from Mill Brook was 18% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for one hydrologic year beginning September and ending in August (low flow to low flow) was 17,363 m^3/day compared to the long term average flows determined by the USGS modeling effort (21,213 m^3/day). The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Mill Brook discharging from upper portion of the sub-watershed and the small freshwater impoundment up-gradient of the stream gauge is mainly due to inter-annual variation in precipitation and is consistent with long term average flow developed by Dr. Kent Healy (retired engineer and resident of Martha's Vineyard). All indications are that the Brook is capturing the up-gradient recharge (and loads) accurately. The MEP determined flow was independently confirmed by comparison to historic Mill Brook flows determined by Dr. Healy. The historic flows measured in Mill Brook ranged from a maximum of 25,819 m3/d to a minimum of 5,350 m3/d with a 15 year average flow of 14,600 m3/d. The MEP determined average daily flow based on stream gaging over the course of a complete hydrologic year was 16 percent higher compared to the historic flows but well within the range (see Section III).

Table IV-3. Comparison of water flow and nitrogen load discharged by River and Brook (freshwater) to the Town Cove portion of the Tisbury Great Pond Embayment System. The "Stream" data are from the MEP stream gauging effort. Watershed data are based upon the MEP watershed land-use modeling effort (Section IV.1) and the USGS watershed delineation (Section III).

Stream Discharge Parameter	Mill Brook Discharge[(a)] Tisbury Great Pond	Tiasquam River Discharge[(a)] Tisbury Great Pond	Data Source
Total Days of Record	365[(b)]	365[(c)]	(1)
Flow Characteristics			
Stream Average Discharge (m3/day)	17,363	12,191	(1)
Contributing Area Average Discharge (m3/day)	21,213	14,416	(2)
Discharge Stream 2004-05 vs. Long-term Discharge	18.15%	15.43%	
Nitrogen Characteristics			
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.048	0.047	(1)
Stream Average Total N Concentration (mg N/L)	0.491	0.450	(1)
Nitrate + Nitrite as Percent of Total N (%)	10%	10%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	8.52	5.49	(1)
TN Average Contributing UN-attenuated Load (kg/day)	9.10	5.85	(3)
Attenuation of Nitrogen in Pond/Stream (%)	6%	6%	(4)

(a) Flow and N load to streams discharging to Town Cove / Tisbury Great Pond includes apportionments of Pond contributing area
(b) September 1, 2005 to August 31, 2006.
(c) September 1, 2005 to August 31, 2006.
(1) MEP gage site data
(2) Calculated from MEP watershed delineations to ponds upgradient of specific gages;
the fractional flow path from each sub-watershed which contribute to the flow in the streams to TGP;
and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates.
(4) Calculated based upon the measured TN discharge from the rivers vs. the unattenuated watershed load.

Table IV-4. Summary of annual volumetric discharge and nitrogen load from Mill Brook and the Tiasquam River inflows to Town Cove (head of Tisbury Great Pond estuary based on data presented in Figures IV-6 and IV-7 and Table IV-3.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Tisbury Great Pond (Town Cove) Mill Brook MEP	**September 1, 2005 to August 31, 2006**	**6,337,418**	**306**	**3111**
Tisbury Great Pond (Town Cove) Mill Brook MVC	Based on Watershed Area and Recharge	**7,742,745**	--	--
Tisbury Great Pond (Town Ove) Tiasquam River MEP	**September 1, 2005 to August 31, 2006**	**4,449,539**	**209**	**2003**
Tisbury Great Pond (Town Ove) Tiasquam River MVC	Based on Watershed Area and Recharge	**5,261,840**	--	--

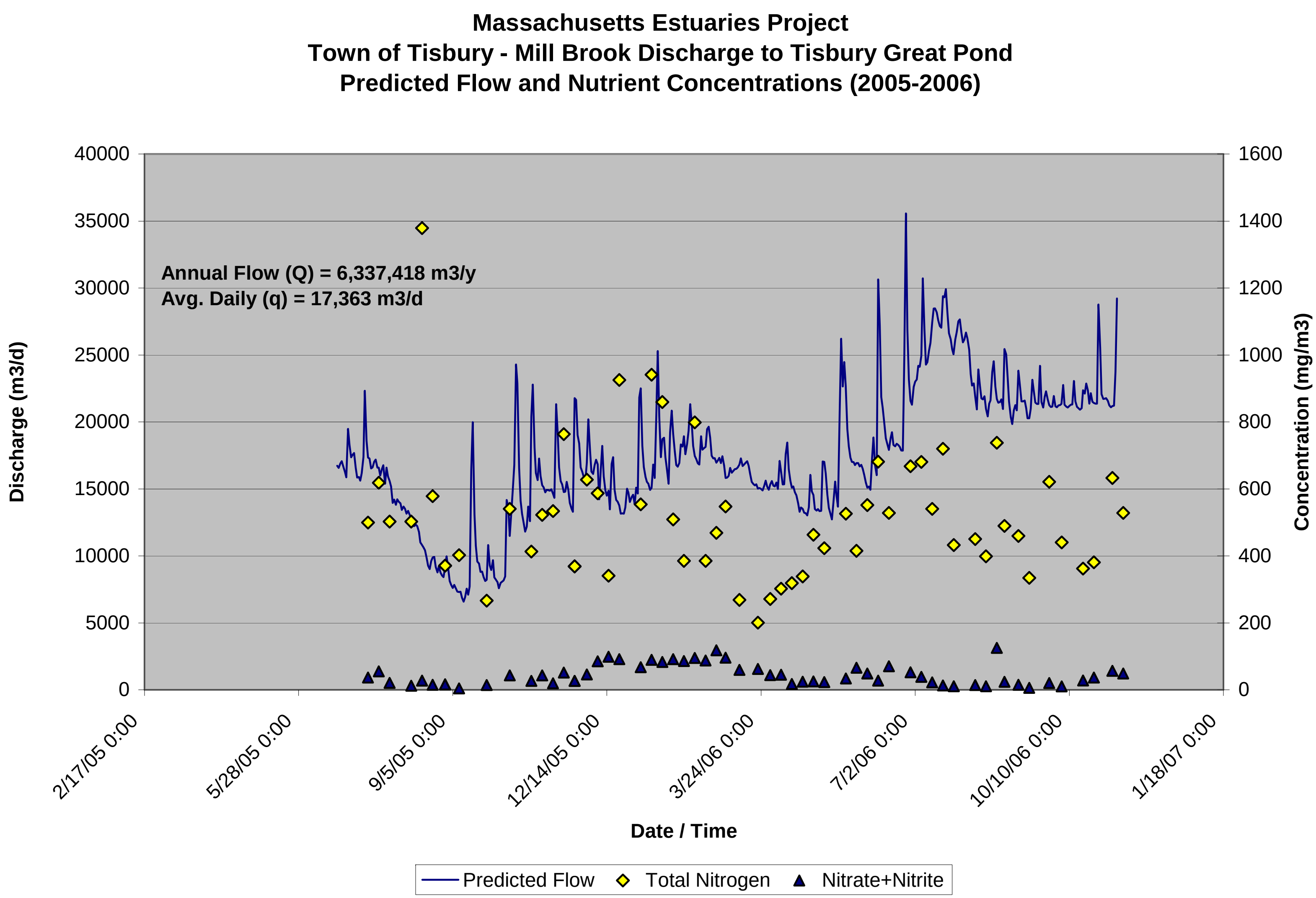

Figure IV-6. Mill Brook discharge (solid blue line), nitrate+nitrite (blue triangle) and total nitrogen (yellow diamond) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Tisbury Great Pond (Table IV-3).

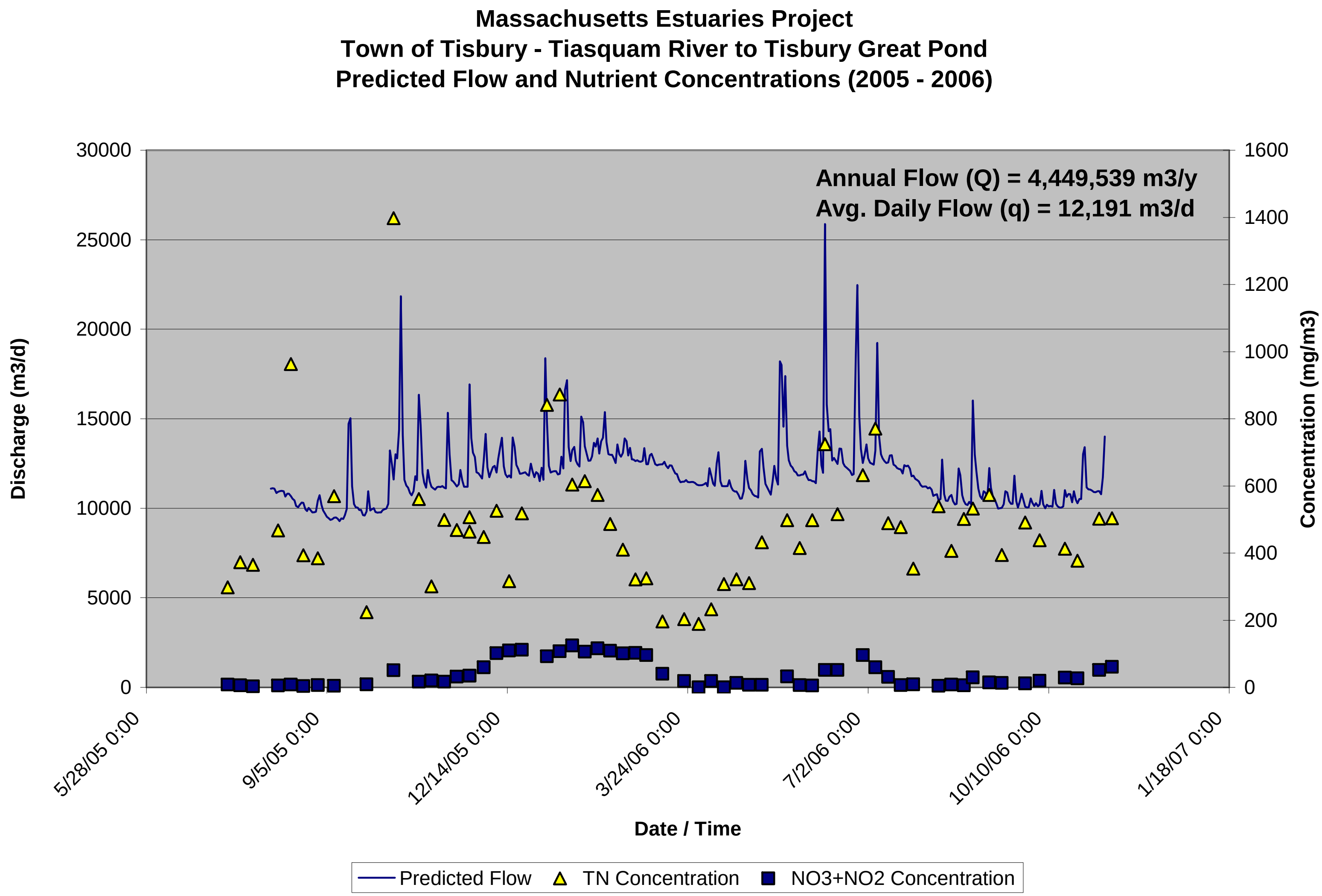

Figure IV-7. Tiasquam River discharge (solid blue line), nitrate+nitrite (blue square) and total nitrogen (yellow triangles) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Town Cove portion of the Tisbury Great Pond system (Table IV-3).

Total nitrogen concentrations within the Mill Brook outflow were moderate, 0.491 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 8.52 kg/day and a measured total annual TN load of 3,111 kg/yr. In Mill Brook, nitrate made up a very small fraction of the total nitrogen pool (10%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the Brook was significantly taken up and converted to organic forms by plants within the pond and/or stream ecosystems. This is seen in the particulate and dissolved organic nitrogen together accounting for 84 percent of the total nitrogen pool and of that 84 percent the vast majority (72%) was dissolved organic nitrogen. Given the low level of remaining nitrate in the stream discharge suggests that very little additional uptake of inorganic nitrogen by the freshwater system could be achieved without modification of the Pond or other up gradient aquatic features.

From the measured nitrogen load discharged by Mill Brook to the estuarine waters of Town Cove and the nitrogen load determined from the watershed based land use analysis, it appears that there is little nitrogen attenuation of watershed derived nitrogen during transport to the estuary. The total nitrogen load (3,111 kg yr^{-1}) discharged from the freshwater Mill Brook to Town Cove compared to that added by the various land-uses to the associated watershed (3,321 kg yr^{-1}), indicates that the integrated attenuation during surface water transport is only 6% (i.e. 6% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the nature of the network of up gradient ponds capable of attenuating nitrogen as well as the high water turnover within Mill Pond (<1 day). The directly measured nitrogen load from the brook was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

IV.2.3 Surface Water Discharge and Attenuation of Watershed Nitrogen: Tiasquam River discharge to Town Cove Portion of Tisbury Great Pond

Looks Pond, located up gradient of the Tiasquam River gauge site (South Road crossing) is a small freshwater pond and unlike many of the freshwater ponds on Martha's Vineyard and Cape Cod, this pond has stream outflow rather than discharging solely to the aquifer along its down-gradient shore. This stream outflow, the Tiasquam River, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the sub-watershed nitrogen load to the estuary and the level of nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands, small impoundments and streambed associated with the Tiasquam River. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the Tiasquam River above the gauge site and the measured annual discharge of nitrogen to the tidal portion (when the pond is breached) of the Town Cove portion of the Tisbury Great Pond system, Figure IV-5.

At the Tiasquam River gauge site, a continuously recording vented calibrated water level gauge was installed to yield the level of water in the lower reach of the freshwater portion of the Tiasquam River. As the Town Cove portion of the Tisbury Great Pond system is tidally influenced at times when the pond if breached, the gauge was located as far down gradient along the Tiasquam River reach such that a complete measure of attenuation in the sub-watershed could be obtained and also such that freshwater flow could be measured at low tide during breach events and at high stand when the pond was closed. To confirm that freshwater flow was being measured, the stage record was analyzed for any tidal influence during the deployment period and salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average salinity during the entire deployment period was determined to be 0.1 ppt. Therefore, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked monthly. The gauge on the Tiasquam River was installed on June 20, 2005 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued until November 9, 2006 for a total deployment of 17 months.

Surface freshwater flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Tiasquam River site based upon these flow measurements and measured water levels at the gauge site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge to the head of the Town Cove portion of the Tisbury Great Pond Embayment System, immediately south of the South Road bridge crossing, and reflective of the biological processes occurring in the stream channel and small up-gradient impoundment (Look Pond) contributing to nitrogen attenuation (Figure IV-7 and Tables IV-3 and IV-4). In addition, a water balance was constructed based upon the U.S. Geological Survey confirmed groundwater flow model to determine long-term average freshwater discharge expected at each gauge site.

The annual freshwater flow record for the Tiasquam River measured by the MEP was compared to the long-term average flow determined by the groundwater modeling effort (Table III-1). The measured freshwater discharge from the Tiasquam River was 15% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for one hydrologic year beginning September and ending in August (low flow to low flow) was 12,191 m^3/day compared to the long term average flows from the watershed water balance which indicates a long-term average daily flow of 14,416 m3/d. The small difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the Tiasquam River discharging from the upper portion of the sub-watershed and the small freshwater impoundment up-gradient of the stream gauge falls within the acceptable range resulting from inter-annual differences in precipitation and groundwater levels (see also Section III). These results are also consistent with long term average flow developed by Dr. Kent Healy (retired engineer and resident of Martha's Vineyard). Again, this supports the contention that the River gauge site is capturing the up-gradient recharge (and loads) accurately. This long-term Tiasquam River flow record ranged from a maximum of 13,699 m3/d to a minimum of 37.5 m3/d with a 15 year average flow of 8,203 m3/d. The MEP determined average daily flow based on continuous recording for 1 water year was 48 percent higher but within the range. Taking into consideration the Mill Brook and Tiasquam flows together, historical measurements (1994-2008) yielded a maximum flow of 38,999 m3/d and a minimum flow of 9,924 m3/d with an overall average flow of 22,640 m3/d. By comparison the MEP determined combined flow for surface water entering Town Cove (Mill Brook + Tiasquam River) was 29,553 m3/d was in the range, but higher than the historic flows, but lower than the watershed water balance which indicates a long-term average daily combined discharge of 35,629 m3/d.

Similar to Mill Creek, the total nitrogen concentrations in the Tiasquam River outflow were moderate, 0.450 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 5.49 kg/day and a measured total annual TN load of 2,003 kg/yr. As with Mill Brook, in the Tiasquam River, nitrate made up a very small fraction of the total nitrogen pool (10%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the River was significantly taken up and converted to organic forms by plants within the pond and/or stream ecosystems. This is seen in the particulate and dissolved organic nitrogen data which together accounted for 86 percent of the total nitrogen pool and of that 84 percent the vast majority (73%) was dissolved organic nitrogen. Given the low level of remaining nitrate in the stream discharge suggests that very little additional uptake of nitrogen by the freshwater system could be achieved without some modification of the Pond or other up gradient aquatic features.

From the measured nitrogen load discharged by the Tiasquam River to the Town Cove portion of the Tisbury Great Pond estuary and the nitrogen load determined from the watershed land use analysis, it appears that there is only a slight attenuation of nitrogen during transport from upland sources to the estuary. Based upon lower total nitrogen load (2,003 kg yr^{-1}) discharged from the freshwater Tiasquam River compared to that added by the various land-uses to the associated watershed (2,135 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 6% (i.e. 6% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the nature of the network of few up gradient ponds capable of attenuating nitrogen and is also consistent with the limited attenuation observed in the adjacent Mill Brook system. The directly measured nitrogen load from the brook was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

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

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

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

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

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

IV.3.2 Method For Determining Sediment-Watercolumn Nitrogen Exchange

For the Tisbury Great 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 were collected from a total of 23 sites throughout the Tisbury Great Pond Embayment System. Cores were collected from 9 sites within the main basin of Tisbury Great Pond, 4 sites from Deep Bottom-Thumb Cove, 1 site in Pear Tree Cove, 3 sites in Tiah Cove, 3 sites in Town Cove and 3 sites in Black Point Pond (Figure IV-8). All the sediment cores for this system were collected in July-August 2005. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

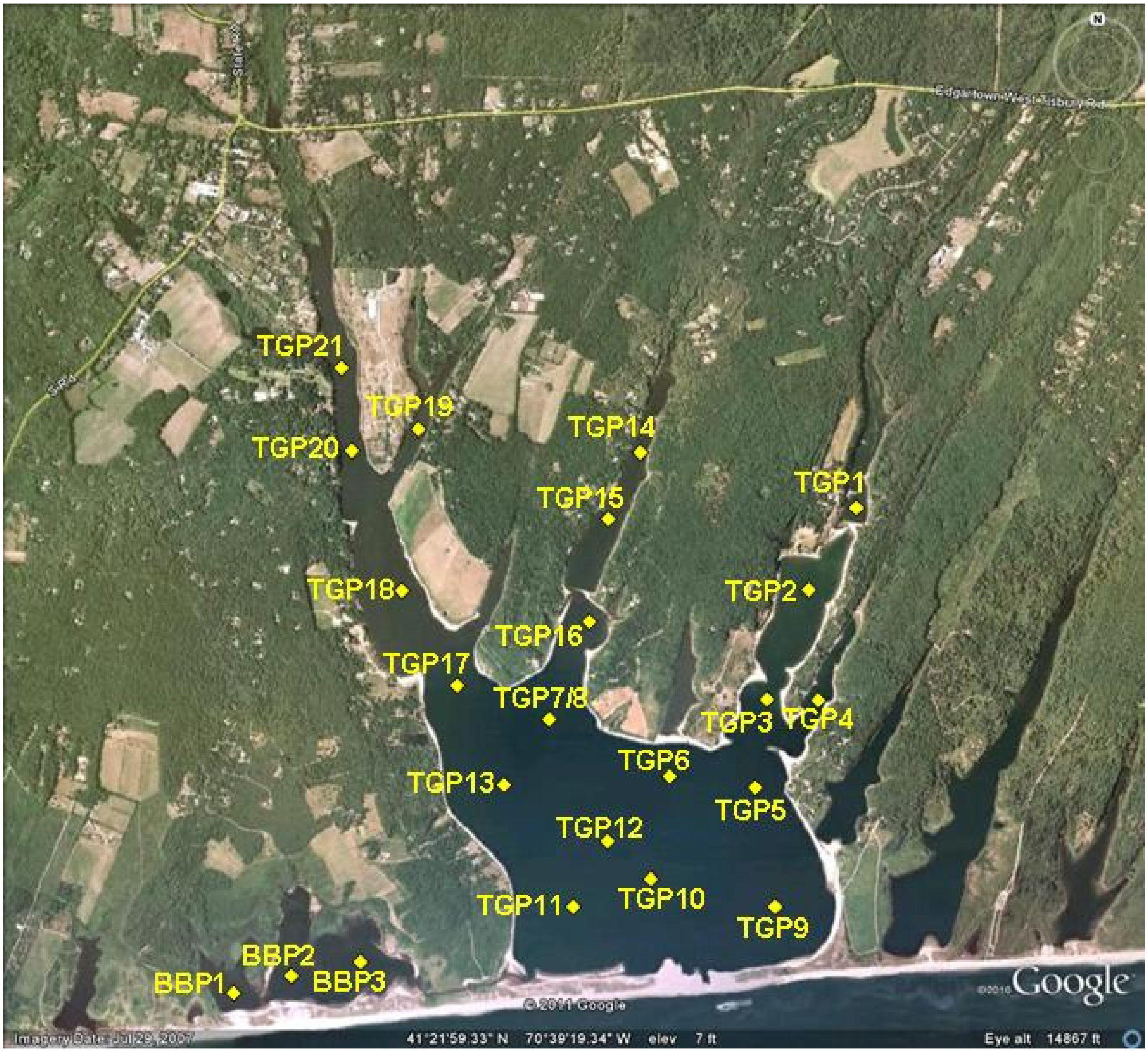

Figure IV-8. Tisbury Great Pond Embayment System sediment sampling sites (yellow symbols) for determination of sediment-water column exchange rates. Numbers are for reference to station identifications listed above and in Table IV-5.

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 shoreside lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from core sites to replace the headspace water of each core prior to incubation. The number of core samples from each estuarine component (Figure IV-8) are as follows:

Tisbury Great Pond Benthic Nutrient Regeneration Cores

• TGP-1	1 core	(Deep Bottom Cove)
• TGP-2	1 core	(Deep Bottom Cove)
• TGP-3	1 core	(Deep Bottom Cove)
• TGP-4	1 core	(Thumb Cove)
• TGP-5	1 core	(Main Basin)
• TGP-6	1 core	(Main Basin)
• TGP-7/8	2 cores	(Main Basin)
• TGP-9	1 core	(Main Basin)
• TGP-10	1 core	(Main Basin)
• TGP-11	1 core	(Main Basin)
• TGP-12	1 core	(Main Basin)
• TGP-13	1 core	(Main Basin)
• TGP-14	1 core	(Tiah Cove)
• TGP-15	1 core	(Tiah Cove)
• TGP-16	1 core	(Tiah Cove)
• TGP-17	1 core	(Main Basin)
• TGP-18	1 core	(Town Cove)
• TGP-19	1 core	(Pear Tree Cove)
• TGP-20	1 core	(Town Cove)
• TGP-21	1 core	(Town Cove)
• BBP-1	1 core	(Black Point Pond)
• BBP-2	1 core	(Black Point Pond)
• BBP-3	1 core	(Black Point Pond)

Sampling was distributed throughout the primary component basins of the Tisbury Great Pond Embayment System and the results were used for calculating the net nitrogen regeneration rates for the water quality modeling effort.

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

Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA (Coastal Systems Analytical Facility, 508-910-6325 or d1white@umassd.edu). The laboratory follows standard methods for saltwater analysis and sediment biogeochemistry.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

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

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

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

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

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can “escape” to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-9).

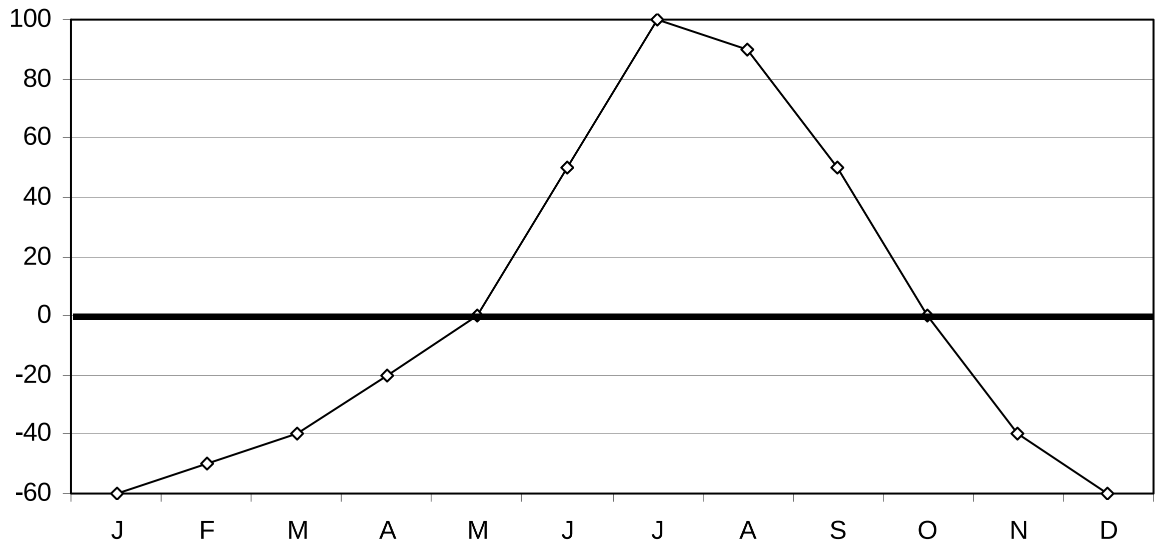

Figure IV-9 Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

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

Sediment sampling was conducted throughout the primary component basins (Tisbury Great Pond-main basin, Deep Bottom & Thumb Coves, Tiah Cove, Town Cove and Black Point Pond), which comprise the overall Tisbury Great Pond Embayment System in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores in each basin was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

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

Net nitrogen release or uptake from the sediments within the Tisbury Great Pond embayment system (808 acres) were comparable to other similar embayments with similar configuration and flushing rates in southeastern Massachusetts, even though this system is not regularly exposed to tidal flushing. There was a clear pattern of sediment N flux, with Town Cove, the initial recipient of almost half of the watershed's discharge of freshwater and nitrogen, showing a low-moderate net release, 23.1 mg N m^{-2} d^{-1}, declining to a relatively consistent rate of 8.8 mg N m^{-2} d^{-1} over the large down-gradient main basin of Tisbury Great Pond (Table IV-5). The smaller tributary coves supported low rates of release and even slight uptake: Pear Tree Cove, Tiah Cove and Deep Bottom/Thumb Cove with rates of 0.1 mg N m^{-2} d^{-1}, -1.6 mg N m^{-2} d^{-1}, and 6.5 mg N m^{-2} d^{-1}, respectively. These rates are consistent with the structure of the basins and the predominance of sediments comprised of soft consolidated mud with an oxidized surface layer generally to ~1 cm depth and the absence of microbial mats and accumulations of drift macroalgae. The highest rates of net nitrogen release were measured in Black Point Pond (64 acres) with its fringing wetlands showing a moderate net release, 36.9 mg N m^{-2} d^{-1}. Although Black Point Pond exchanges nitrogen and organic matter with Tisbury Great Pond, the Crab Creek connecting channel is relatively restricted. The result is that the nitrogen cycle of Black Point Pond is more independent of adjacent water bodies than many estuarine basins.

Sediment nitrogen uptake and release rates in Tisbury Great Pond were similar to many tidal embayments in the region of similar proportions, particularly those within the similarly sized and configured Edgartown Great Pond, located nearby in the same geologic setting. Both Tisbury and Edgartown Great Ponds are dominated by a large open water lagoon, formed behind the barrier beach and both are only periodically open to tidal exchange with the Atlantic Ocean waters. The large main basin of Edgartown Great Pond (15.2 mg N m^{-2} d^{-1}) showed similar low rates of net release as the main basin of Tisbury Great Pond. Also, the five "unrestricted" coves within Edgartown Great Pond generally showed low rates of release and uptake, -16.9 to 7.4 mg N m^{-2} d^{-1} consistent with the eastern coves in Tisbury Great Pond.

Similarly the semi-restricted basin of upper Mashacket Cove[2] showed rates similar to Black Point Pond, 37.6 mg N m^{-2} d^{-1}.

Table IV-5. Rates of net nitrogen return from sediments to the overlying waters of the Tisbury Great Pond Embayment System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Section VI). Measurements represent July -August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			Sta. i.d. *
	Mean	S.E.	# sites	
Tisbury Great Pond Embayment System				
Pear Tree Cove	0.1	0.1	1	TGP-19
Tiah Cove	-1.6	4.6	3	TGP-14,15,16
Deep Bottom-Thumb Cove	6.5	14.9	4	TGP 1,2,3,4
Town Cove	23.1	18.4	3	TGP 18,20,21
Tisbury Great Pond Main Basin	8.8	4.4	10	TGP 5-13,17
Black Point Pond	36.9	27.1	3	BBP 1,2,3

* Station numbers refer to Figures IV-8.

The Tisbury Great Pond Embayment System supports watercolumn-sediment exchange rates that are also consistent with other embayments within the region that are fully open to tidal exchange. For example in the Lewis Bay System the main basin (also a lagoon) averaged 6.9 mg N M^{-2} d^{-1}. The main basin of Madaket Harbor averaged 6 mg N m^{-2} d^{-1} and the similarly configured West Bay (Three Bays, Barnstable) 4.5 mg N m^{-2} d^{-1}. The few analogous basins in open embayments that are similar to the coves within Tisbury Great Pond also show similar low rates of net nitrogen uptake/release from their sediments. For example, Eel River and Prince Cove (Three Bays) -6.4 and 10.3 mg N m^{-2} d^{-1}, The Let (Westport River) 20.5 mg N m^{-2} d^{-1}, and Uncle Roberts Cove (Lewis Bay). Based upon the pattern and rate of net nitrogen uptake/release from the sediments in the main basin and coves of Tisbury Great Pond and Black Point Pond and the comparable rates in analogous basins in other estuaries, the measured rates were used in the water quality modeling effort for the component sub-basins of the Tisbury Great Pond Embayment System (Section VI). The sediments within the Tisbury Great Pond Embayment System appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to this system and periodic exposure to tidal flushing.

System-wide Sediment Nitrogen Release: In a closed basin, such as Tisbury Great Pond, it is possible to determine the system-wide rate of nitrogen return from the bottom sediments based upon time series water-column total nitrogen data and the rate of external nitrogen loading (watershed + atmosphere). In the case of Tisbury Great Pond the external loading rate is relatively low for an embayment of this scale in southeastern Massachusetts (58.1 kg N d^{-1}, see Section IV-1), similar to Edgartown Great Pond (41.4 kg N d^{-1}) but higher than Sesachacha Pond (Nantucket), 4.1 kg N d^{-1}, other periodically opened great salt ponds. For comparison, Lewis Bay, Wareham River and Three Bays estuaries have loading rates on the order of 105.8, 130.3 and 146.4 kg N d^{-1} respectively. The low rate of watershed+atmospheric nitrogen input to Tisbury Great Pond increases the potential sensitivity of using a basin-wide nitrogen mass balance approach to determine the rate of sediment nitrogen flux (Section VI).

[2] Mashacket Cove upper basin was nearly separated by a "shoal" from the rest of the Edgartown Great Pond System creating a distinct sub-basin at the time of the MEP assays.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes field data collection effort and the development of hydrodynamic models for the Tisbury Great Pond system (Figure V-1). For this system, the model offers an understanding of water movement from the pond during and after a breach. It provides the first step towards evaluating water quality, and it is a tool for later determining nitrogen loading "thresholds". Nutrient loading data combined with measured environmental parameters within the system become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing water quality parameters, as well as determining the likely positive impacts of various alternatives for improving health of the pond, facilitating the understanding how pollutant loading into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

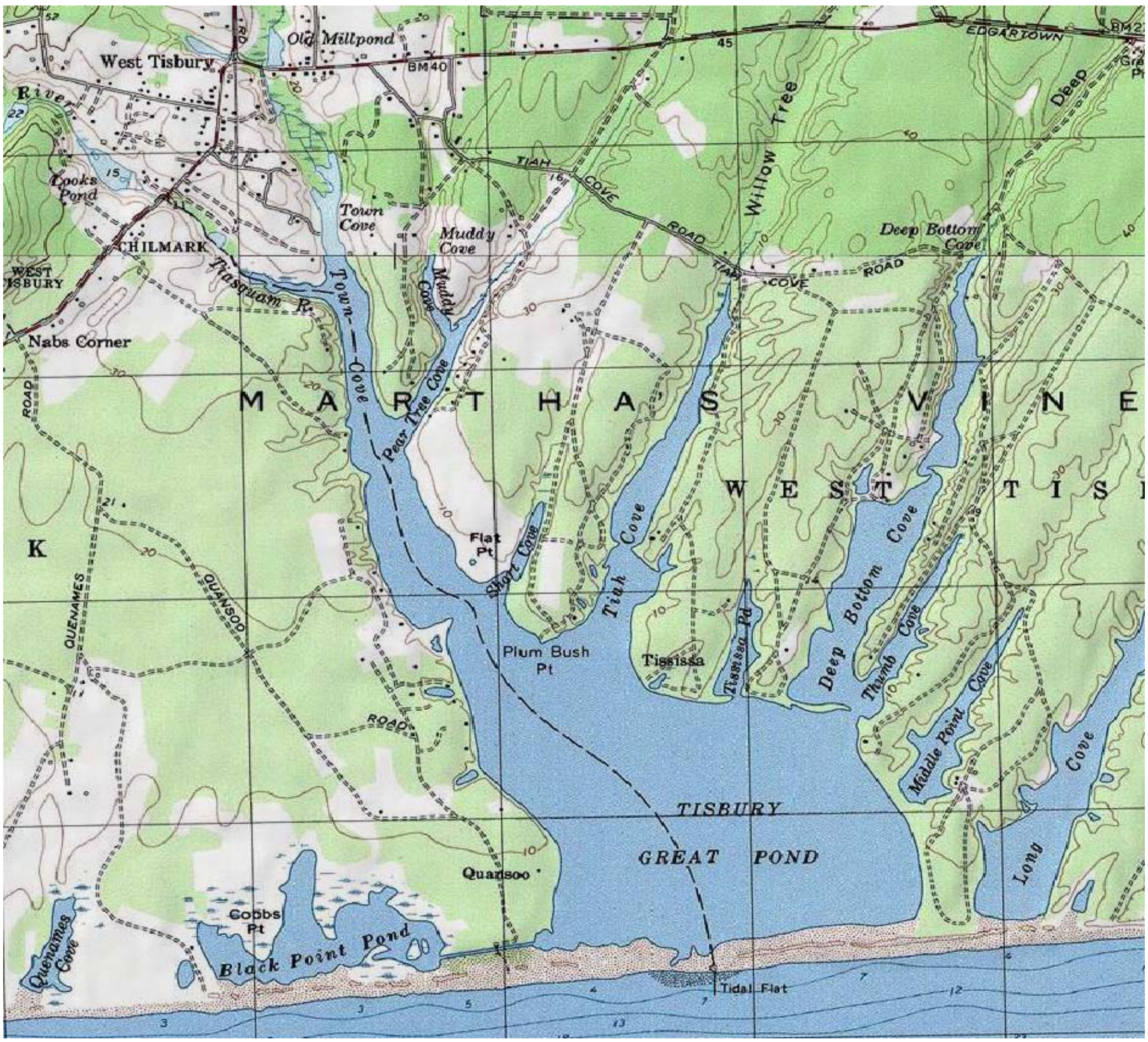

Figure V-1. Location of Tisbury Great Pond on the island of Martha's Vineyard in Massachusetts.

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

Coastal ponds like Tisbury Great Pond are the initial recipients of freshwater flows (i.e., groundwater and surface streams) and the nutrients they carry. An embayment's shape influences the time that nutrients are retained in them before being flushed out to adjacent open waters, and their shallow depths both decrease their ability to dilute nutrient (and pollutant) inputs and increase the secondary impacts of nutrients recycled from the sediments. Degradation of coastal waters and development are tied together through inputs of pollutants in runoff, rainfall and groundwater flows. Excess nutrients, especially nitrogen, promote phytoplankton blooms, with adverse consequences including low oxygen, shading of submerged aquatic vegetation, and aesthetic problems.

V.1.1 System Physical Setting

Tisbury Great Pond is set along the southern shoreline of Martha's Vineyard. The layout of the Tisbury Great Pond system is shown in the topographic map detail of Figure V-1. The pond has a surface area of approximately 845 acres. The pond is fully enclosed, but is periodically opened by means of a trench dug across the beach to drain the pond into the Atlantic Ocean.

Similar systems, sometimes referred to as "blind", "intermittently open", or "seasonally open" estuaries, are also found in Australia, on the west coast of the United States, South America and India (Stretch and Parkinson, 2006). Perched estuaries are those that have water levels consistently above mean sea level (MSL) and tend to occur on coastlines that have an energetic wave climate with steep beaches and coarse sediments. It is common practice to artificially breach closed ponds/estuaries when water levels become high, typically to prevent flooding of upland properties and to flush the systems from a build-up of contaminants adversely impacting water quality. Other coastal ponds along the south coast of Martha's Vineyard, Nantucket, and the southern shoreline of Massachusetts/Rhode Island are local examples of where periodic breaching is a regular facet of pond management.

V.1.2 System Hydrodynamic Setting

In Tisbury Great Pond, the hydrodynamic regime is dominated by freshwater inputs to the system from groundwater recharge, surface flow run-off from the watershed, and direct precipitation to the pond's surface. The volume of water in the pond is governed by the balance between additions from freshwater inflow and losses due to evaporation and flow through the eastern beach face into the ocean. On average, the inputs are greater than the losses and the pond elevation gradually rises.

When the pond level is deemed high enough, a trench is cut across the southern barrier beach. Because the pond level is higher than the ocean, the pond drains. The initial outflow from the pond causes a relatively small channel to be scoured through the beach and the water level in the pond drops. The ephemeral channel across the beach is a balance between the scouring effect of water flowing through it and the filling effect of sediment transport along the beach. Although Tisbury Great Pond is large relative to other regional coastal ponds, the wave climate on the southern coast of Martha's Vineyard is one of the most energetic in Massachusetts. As a result, the breach channel can close quickly, sometimes after only minimal tidal exchange has occurred. These short or failed breaches only remove the top layer of water from the pond, meaning that there is very little inflow of water from the ocean and little mixing of the nutrient rich water from the pond with the low nutrient inflow. As a result, openings that do not allow influx of ocean waters simply lower the water levels and do little to improve the water quality inside the pond.

During the time of this study data collected observes water levels within the estuary after a breach of the barrier beach between the estuary and the ocean was made. For the remainder of observation time period the inlet stayed open, allowing tidal exchange between the estuary and the ocean. According to past data collected (Healy, 2009), the breach observed in this study shows typical conditions of this estuary after a breach has been made where the estuary can remain open for several weeks.

V.1.3 Pond Management Practices

Water levels in Tisbury Great Pond are managed by periodic breaching of the barrier beach. This breaching is done using a backhoe (Figure V-2), similar to other breached ponds on Martha's Vineyard (e.g., Howes, et al., 2007). A diligent record of pond water levels and breachings between 1993 and present is available from Dr. Kent Healy (Healy, 2009 with updates). The record (Table V-1) shows that there are typically three openings made each year, with an average cumulative total of 144 days open each year. The average duration of all openings in this record is 42 days. Some openings last less than a week, while two in the record lasted for approximately 170 days total.

The inlet is breached when water levels are typically higher than 4.1 feet NAVD. This elevation provides an adequate volume of water in the pond to scour initially the inlet channel. Higher pond elevations lead to flooding of low-lying properties and structures around the pond. Though the initial inlet channel cut by the backhoe is approximately 15 feet wide (as observed with the March 2012 breach, Figure V-3), the aerial photograph record shows that the inlet grows to a typical width of around 120 feet.

Table V-1. Annual Great Pond openings between 1993 and 2012, according to Healy (2009).

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Openings	3	4	3	2	3	3	2	3	4	2	5	3	3	5	4	3	4	3	5
Cumulative days opens	123	102	86	224	156	229	55	48	77	218	149	170	230	57	123	154	272	156	118

Figure V-2. Great Pond inlet excavation by a backhoe, March 21, 2012.

Figure V-3. Newly opened inlet Great Pond inlet channel during initial draw-down of pond water levels.

V.2 HYDRODYNAMIC FIELD DATA COLLECTION AND ANALYSIS

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

V.2.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Tisbury Great Pond system was assembled from a recent boat based hydrographic survey and from land based measurements at key locations. The recent survey was executed specifically as part of the Massachusetts Estuaries Project analysis.

The hydrographic surveys conducted on February 22 and February 27, 2012 were designed to cover the entire main basin of Tisbury Great Pond, as well as the various coves within the pond. The survey was conducted from a 14' skiff with an installed precision fathometer (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide horizontal position measurements accurate to approximately 1-3 feet. As the boat was maneuvered around the pond, digital data output from both the echo sounder fathometer and GPS were logged to a laptop computer, which integrated the data to produce a single data set consisting of water depth as a function of geographic position. Land based measurements were conducted in shallow areas where high bathymetric resolution would be beneficial to the model, using the same GPS system.

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to the North American Vertical Datum of 1988 (NAVD) vertical datum. Once rectified, the finished processed data were archived as 'xyz' files containing x-y horizontal position (in Massachusetts State Plan 1983 coordinates) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The tracks followed by the boat during the bathymetry survey are presented in Figure V-4.

V.2.2 Tide Data

Tide data records were collected at two locations in the Tisbury Great Pond system: Black Pond and Town Cove. The locations of these stations are shown in Figure V-4. At each station Temperature Depth Recorders (TDR) were deployed to record the water level data. They were deployed for a 24-day period between March 22 and April 15, 2012. Data from the Martha's Vineyard Coastal Observatory (MVCO) offshore of South Beach was used as the offshore boundary condition for this hydrodynamic study.

Once the data from each estuary station were downloaded from the instruments, pressure data were corrected for variations in atmospheric pressure. Hourly atmospheric pressure readings were obtained from the NOAA station in Nantucket Sound (44020), interpolated to 10-minute intervals, and subtracted from the pressure readings, resulting in variations in water pressure above the instrument. A (constant) water density value of 1025 kg/m^3 was applied to the readings to convert from pressure units (psi) to head units (for example, feet of water above the tide gauge). The elevation of the pressure port of each TDR was measured using an RTK GPS unit. These surveyed elevations were used to adjust the water surface to the NAVD 88 vertical datum. The result from each gauge is a time series record representing the variations in water surface elevation relative to a known datum. A plot of the water levels following the March 2012 breach is shown in Figure V-5.

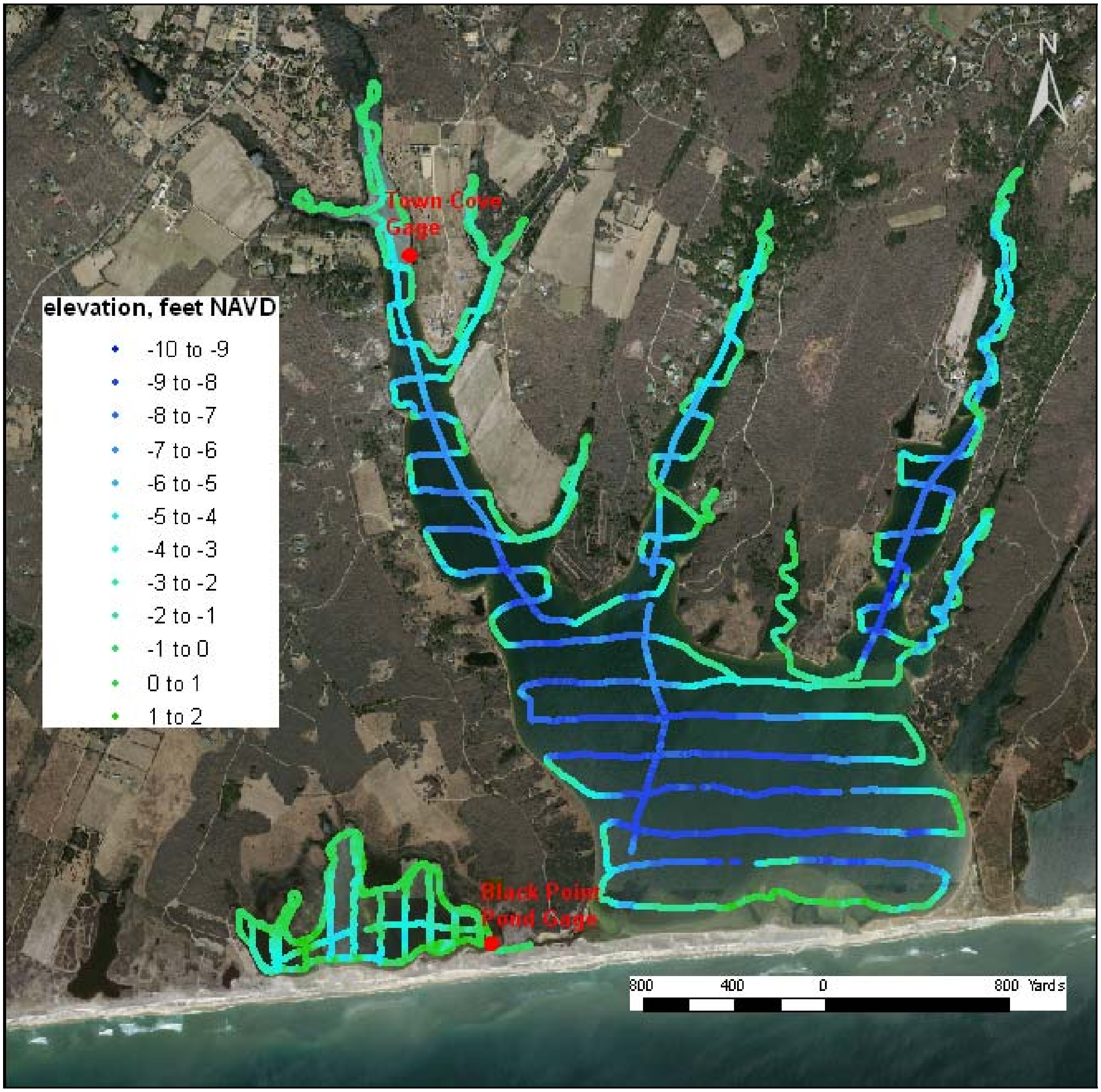

Figure V-4. Bathymetry survey lines (blue/green) and tide locations (red) in Tisbury Great Pond.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the records. These datums are presented in Table V-2. 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.

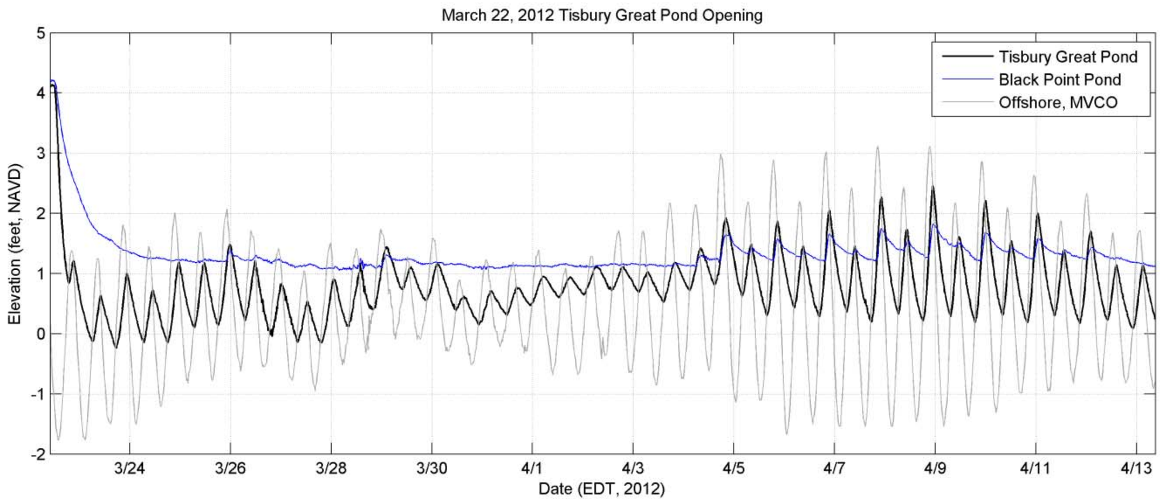

Figure V-5. Observed water levels during the March 22nd breach event, then the observed tidal signal in the Tisbury Great Pond System afterwards. The MVCO offshore station is included (grey).

Table V-2. Tide datums computed from 19-day records collected offshore and in the Tisbury Great Pond System starting on March 25 2012. Datum elevations are given relative to NAVD vertical datum.

Tide Datum	MVCO Offshore Station (feet)	Town Cove (feet)	Black Point Pond (feet)
Maximum Tide	3.1	2.5	1.8
MHHW	2.1	1.5	1.4
MHW	1.9	1.3	1.3
MTL	0.5	0.8	1.3
MLW	-1.0	0.3	1.2
MLLW	-1.0	0.2	1.2
Minimum Tide	-1.8	-0.2	1.1
Mean Range	2.9	1.0	0.1

Figure V-5 and TableV-2 show a large difference between the tidal range offshore and within the system. At Town Cove the mean tide range is 1.9 feet less than and only 36% of the mean tide range of the offshore data. In Black Point Pond the mean tide range is only 5% of the offshore mean tide range. These losses of amplitude are described as tidal attenuation, caused by frictional damping within the system. Furthermore, at Black Point Pond the mean tide level is significantly higher than it is offshore, indicating that it does not drain well into the remainder of the Tisbury Great Pond system. A large portion of the attenuation and higher mean tide level in Black Point Pond is caused by frictional losses and damming of water by the sand flats at the eastern entrance of Crab Creek which connects the two bodies of water.

A harmonic analysis of the tidal time series was also performed to produce tidal amplitude and phase of the major tidal constituents, and provide assessments of hydrodynamic 'efficiency' of the system in terms of tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each system. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The observed astronomical tide is the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-6. The amplitudes and phase of 21 known tidal constituents result from this procedure. Table V-3 presents the amplitudes of seven tidal constituents computed for the Tisbury Great Pond station records for the entire time series excluding the period of time immediately after the breach where the tidal influence was minimal.

An analysis of the entire MVCO offshore record yields that the M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an offshore amplitude of 1.3 feet. The total range of the M_2 tide is twice the amplitude, or 2.6 feet. This constituent is the largest contributor to the tide throughout the system. The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.14 feet and 0.18 respectively. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, also contribute to the total tide signal, with amplitudes of 0.35 feet and 0.41 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), resulting from frictional attenuation of the M_2 tide in shallow water. The emergence of these residual tides may be seen within the decay of constituents at the Town Cove and the Black Point Pond stations. While all constituents within the system decay, these M_4 and M_6 constituents decay less, resulting from an energy transfer from the M_2 constituent. Overall, it can be seen that as the total tide range is attenuated through the system there is a corresponding reduction in the amplitude of all of the individual tide constituents.

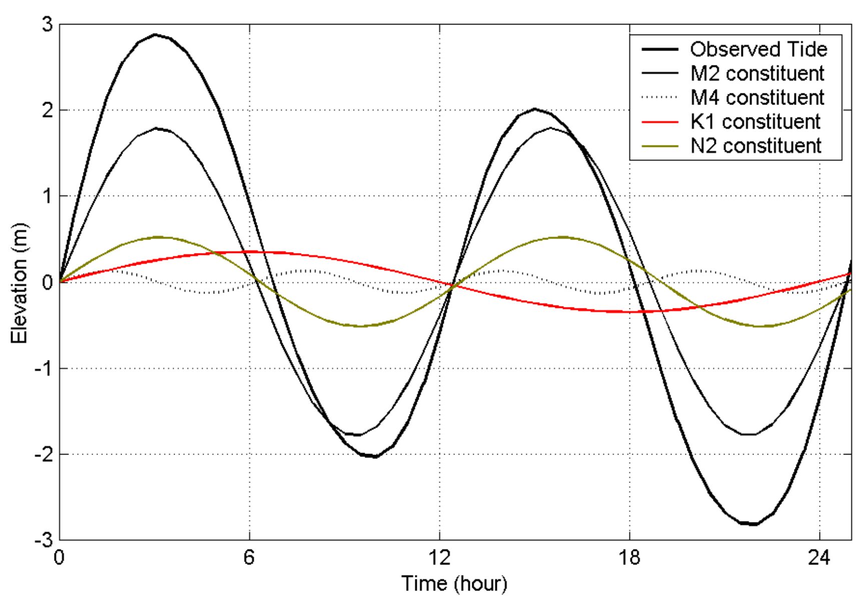

Figure V-6. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-3. 22 Tidal Constituents computed for tide stations in the Tisbury Great Pond system and offshore in Nantucket Sound, March 30 to May 2, 2012.

	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	12.66	23.93	25.82
MVCO Station	1.28	0.11	0.04	0.35	0.41	0.14	0.18
Town Cove	0.44	0.10	0.01	0.15	0.12	0.10	0.11
Black Point Pond	0.05	0.02	0.01	0.03	0.04	0.03	0.04

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 the gauge records in Tisbury Great Pond compared to the energy content the astronomical tidal signal (re-created by summing the contributions from the constituents determined by the harmonic analysis) is presented in Table V-4. Subtracting the tidal signal from the original elevation time series results in the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary. Figure V-5 shows the comparison of the measured tide from the MCVO station, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

Table V-4 shows this analysis done for the entire record and also the period when the inlet to the Great Pond was at its most stable and Black Point Pond was tidal (April 4 through April 13). In order to perform this shortened analysis, fewer tidal constituents were considered because of the time resolution of the tidal data. Therefore the harmonic analyses done in Table V-4 considers only the 7 most prevalent constituents. Because only 7 of the 21 constituents were used, non-tidal influence is likely over estimated. However the remaining constituents not evaluated contribute to only a small amount to the tidal signal and this analysis is suitable.

As seen in the results presented in Table V-4 shows that the variance of tidal energy was largest in the offshore signal, as should be expected. The analyses also show that tides are responsible for at least 95% of the water level changes at the MCVO station. However non-tidal influence is quite large within the system in sections of the data. This may be related to effects caused by changes of the recently formed channel. The non-tidal influence is particularly prevalent between March 31 and April 4. A visual inspection of Figure V-7 shows that during this time period the mean tide level at Town Cove increases while the mean tide level of the offshore gage does not. This effect is likely the result of changes in the inlet to the system. Tidal flow through the channel may have been impeded during this time.

In the second half of Table V-4 the variance analysis is conducted during a time in the data when the inlet was well equilibrated and Black Point Pond is tidal. Additionally the offshore tidal signal shows a period of spring tides during this evaluation. Therefore this time period represents the most tidally dominated portion of the data and it represents the estuary under the most ideal conditions for flushing available within the data. This table shows that, under these conditions, the measured areas are influenced predominantly by astronomical tides and reasonably short flushing times within the system are likely. The non-tidal residual during this time is largest by percentage (more than 30% of the total water level fluctuation) in Black Point Pond, where the greatest tide attenuation occurs.

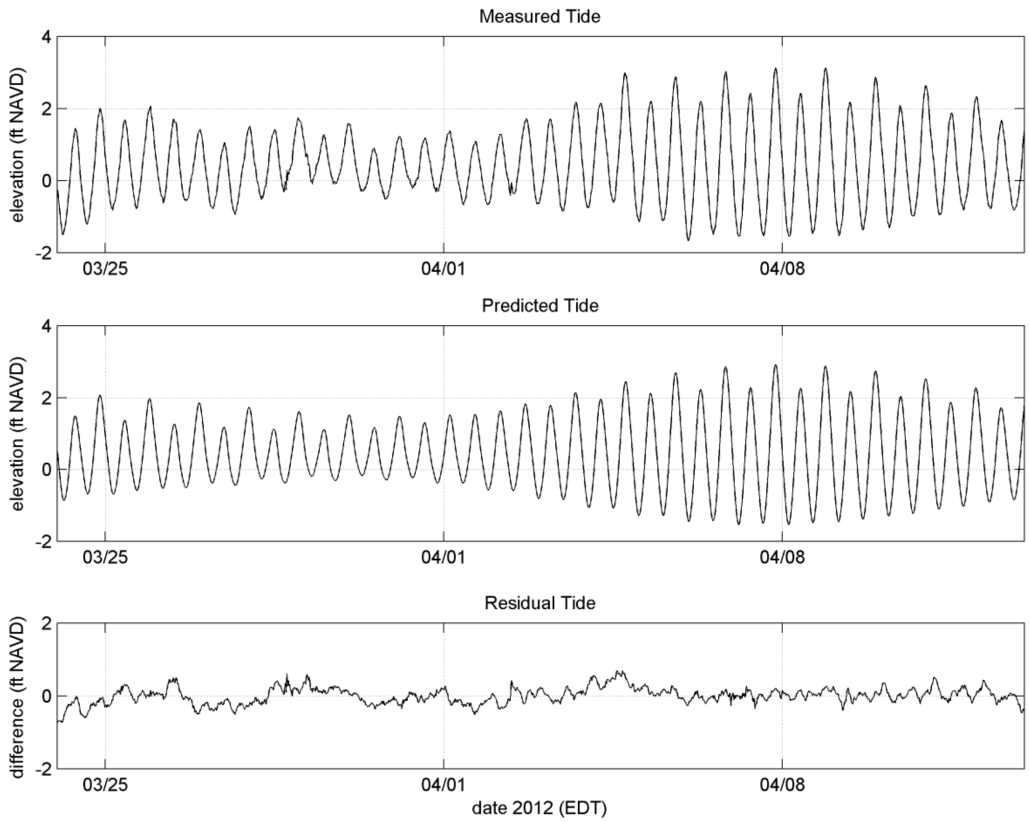

Figure V-7. Measured tide from the MCVO station, with the computed 22 components of astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual water level.

Table V-4. Percentages of Tidal versus Non-Tidal Energy using a seven constituent analysis for the full record, for the complete record, and the period when Black Point Pond was tidal (4/4 through 4/13)

TDR Location	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Complete record			
Offshore	1.08	95	5
North	0.21	65	35
Black	0.02	19	81
April 4 through April 13			
Offshore	1.74	99	1
North	0.28	94	6
Black	0.02	69	31

V.3 HYDRODYNAMIC MODEL DEVELOPMENT

The formation and final dimensions (width and depth) of the inlet channel through the beach, during the initial draw down of the pond after the inlet is dug by the backhoe, cannot be directly simulated with the RMA suite of models. Therefore, a computer model independent of RMA-2 was used to estimate the inlet channel evolution. The final equilibrated dimensions of the inlet channel determined using this model were used in the development of the hydrodynamic numerical model of the system.

V.3.1 Modeling flow through a breach

When the pond is first opened, the initial trench cut through the beach is scoured out by the rush of water leaving the pond. The channel increases in width and depth during this time and over the first few tides cycles. It would be beyond the scope of this study to model the dynamic growth of the channel during the breach event itself. However, the width and depth of the channel are important variables needed to model the flow between the ocean and Tisbury Great Pond.

To assist in the determination of the equilibrium size of the Tisbury Great Pond breach, inlets from past breachings were examined using the available historical aerial photographic record. A survey of the aerial record shows that the equilibrated inlet channel width is approximately 120-feet-wide, on average. This average width was used to determine the channel scour depth.

To estimate the channel scour depth, the flow rate through the channel is needed. Using the data from the March 2012 breach event and the surface area of the Pond (Healy, 2009) the average maximum flow rate out of the pond was determined to be 2,800 ft^3/sec.

With the flow rate and channel width established, the channel depth was calculated using an approach described by the U.S. Army Corps of Engineers (USACE) for the analysis of scour depth at tidal inlets (Hughes, 1999). This equation predicts the depth of the channel, given the flow rate, sediment type and channel width as

$$h = \frac{0.234 q^{8/9}}{\left[g(S-1)\right]^{4/9} d^{1/3}}$$

where *h* is the elevation of the channel bottom relative to the high water level, *q* is the flow rate divided by the channel width, *S* is the specific gravity of the sand and *d* is the average diameter of the sand. A quartz sand (*S* = 2.65) of diameter 0.4mm was used to represent the sand in this case. Using this equation and stated parameters, an equilibrium channel elevation of -1.3 feet NAVD is calculated.

With the initial pond elevation, offshore tides, channel width, and channel depth established, it is possible to compute water levels in the pond through the draw-down period of the pond after the initial breaching of the inlet and the following period when the pond is open to the ocean and tidal. This computed water level time series can then be compared to the actual measured tide in the pond in order to evaluate whether the channel dimensions determined using the USACE equation has produce a useful result that can be used in the development of the RMA-2 hydrodynamic model mesh. To compute a water level time series in the pond, the equation of flow over a broad-crested weir was employed (as described by Hughes, 1999). This equation relates the flow rate through the channel to the channel width and height of water above the channel bottom as

$$Q = 3.0bH^{3/2}$$

where *Q* is the predicted flow rate, *b* is the channel width and *H* is the difference in elevation between the high water and the channel bottom.

Using the starting pond level of 4.2 feet NAVD (measured just prior to the March 2012 breach) and the recorded offshore tides, a computer model was created to calculate the time-varying flow through the channel. The pond level and offshore tide every 10 minutes was input into the model and the flow rate was calculated. Multiplying the flow rate by the time step yields the total volume of water moving through the channel. Knowing the surface area of the pond, the change in pond surface elevation is calculated at each time step.

The comparison between the field data and the broad-crested weir model is shown in Figure V-8 below. It is seen that during the period between March 28 and April 5, the offshore ocean tide was passing through a neap-tide phase. It is apparent that the inlet was having some difficulty remaining open at this time due to the likely combination of a stormy period in the last days of March and also the reduced offshore neap tide range since there is a significant divergence between the model output and measurements. However, with the start of the larger bi-monthly spring tides occurring after April 5, the weir model output and measurements compare very well again. This indicates that the greater spring tide velocities through the inlet were able to able to re-establish an efficient channel.

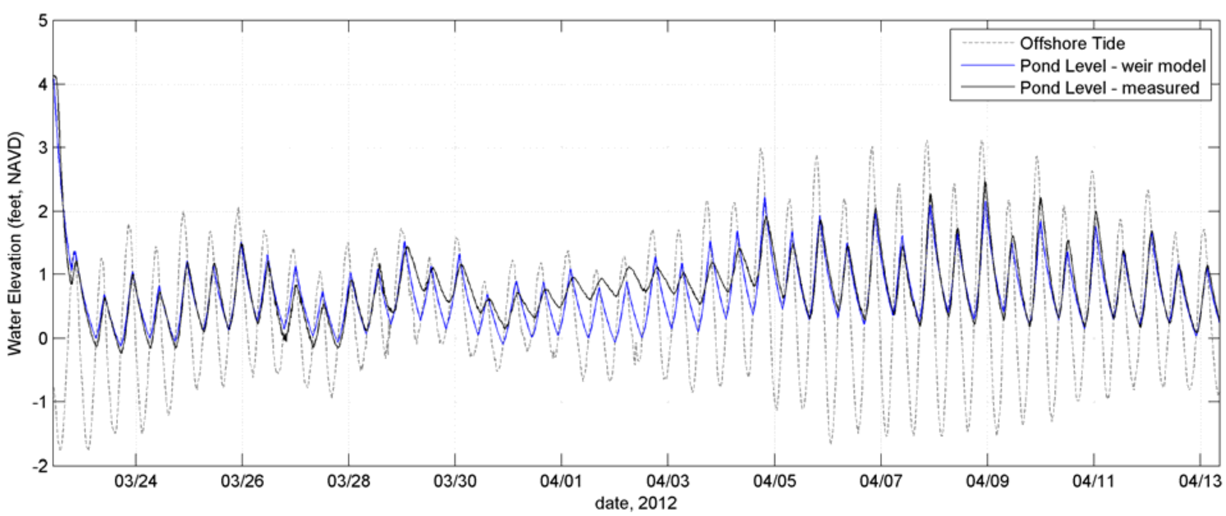

Figure V-8. A comparison of the broad-crested weir model results with the recorded pond elevations during the March 2012 breach event at Tisbury Great Pond.

Model R^2 correlation and RMS error were calculated for the two periods when the inlet was open and flushing efficiently enough to maintain the equilibrium dimensions of the inlet. For the first six-day period starting with the inlet breaching, the R^2 correlation between measurements and model output is 0.94 and the RMS error is 0.14 feet. For the second eight-day comparison period between April 5 and the end of the measured data record at the morning of April 13, the R^2 correlation and RMS error are 0.94 and 0.13 feet, respectively. These comparisons show that the dimensions of the equilibrated inlet channel determined from the aerial record and using the USACE scour depth methodology do provide a useful approximation that can be used to develop the inlet included in the RMA-2 hydrodynamic model mesh.

V.3.2 RMA-2 Model Theory

Applied Coastal utilized a state-of-the-art computer model to evaluate tidal flushing during periods when Tisbury Great Pond is open to the Atlantic Ocean. 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).

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 Surface water 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.3.3 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 2009 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 Tisbury Great Pond grid based on the offshore MCVO tide data. 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.3.3.1 Grid generation

The grid generation process was aided by the use of the SMS package. 2009 digital aerial orthophotos and the 2012 bathymetry survey data were imported to SMS, and a finite element grid was generated to represent the estuary. The aerial photographs were 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 6647 nodes, which describe 2530 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth within the pond is -8.7ft (NAVD). The bathymetry of the completed model grid mesh of the Tisbury Great Pond system is shown in Figure V-9. As described previously in this section (V.4.1), the inlet width and depth used in the model are based on the available aerial photographic record and the results of the USACE weir model computations. The final grid mesh is shown in Figure V-10.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Tisbury Great 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.3.3.2 Boundary condition specification

Three types of boundary conditions were employed for the RMA-2 model of the Tisbury Great Pond system: 1) "slip" boundaries, 2) tidal elevation boundaries, and 3) constant flow input boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. A tidal boundary condition was specified at the inlet from the Atlantic Ocean. TDR measurements provided the required data. The rise and fall of the tide in the ocean 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 Tisbury Great Pond grid every model time step. The model runs of Tisbury Great Pond used a 10-minute time step, which the same as the 10-minute sampling rate of the measured tide data. Details concerning the constant flow input boundary conditions included in the hydro model are discussed in Chapter VI.

V.3.3.3 Calibration

After developing the finite element grids, and specifying boundary conditions, the model for the Tisbury Great 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. The complete model simulation covers a 26-day period from the point where the pond is flushing tidally after the March 21 breach until the end of the measured data record. From full length of the model simulation, shorter periods were used to calibrate and corroborate (verify) the model's performance.

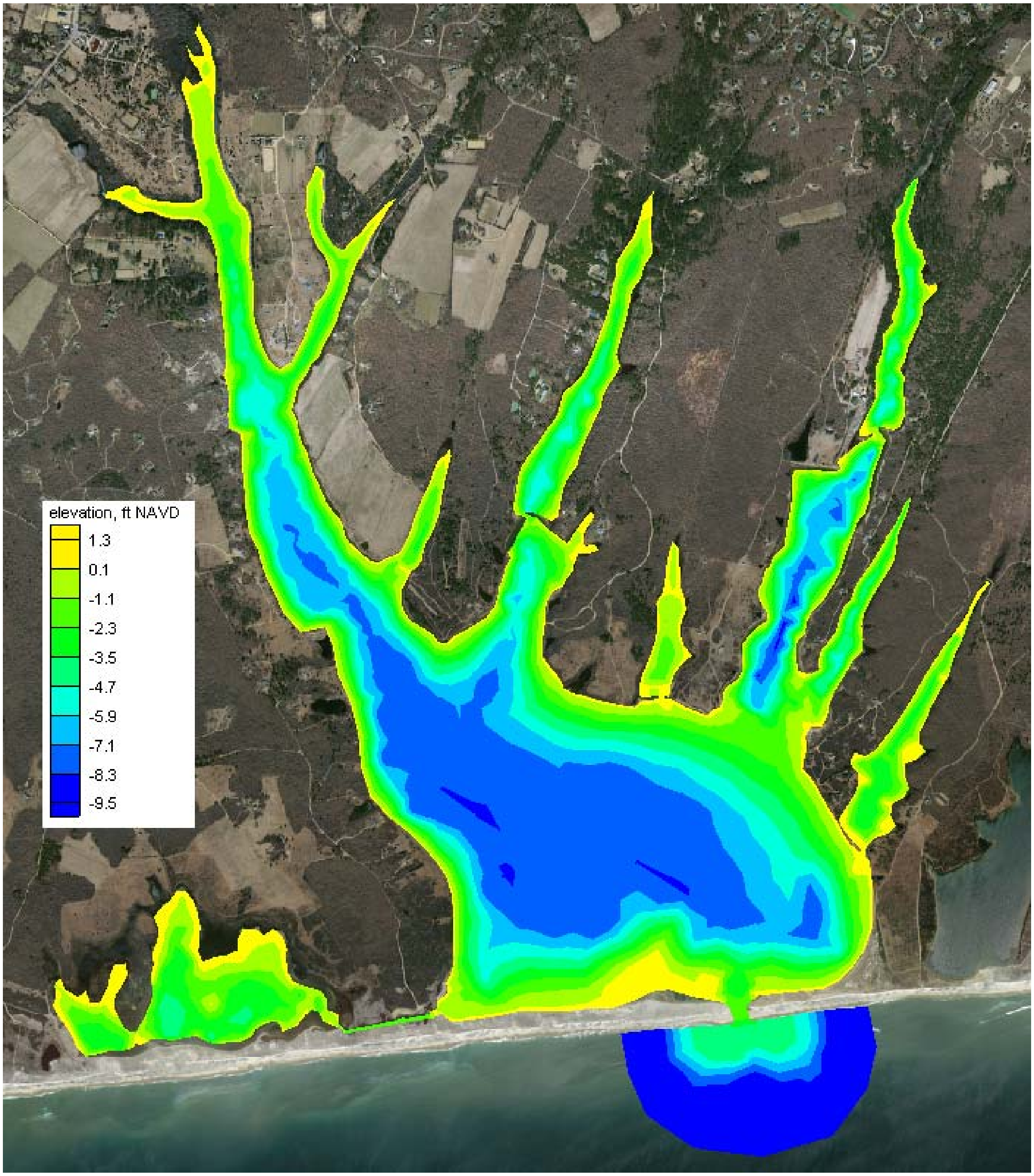

Figure V-9. Bathymetry data interpolated to the finite element mesh used with the RMA-2 hydrodynamic model. Contours represent the bottom elevation relative to North American Vertical Datum 1988. The primary data sources used to develop the grid mesh are the February 2012 surveys of the system.

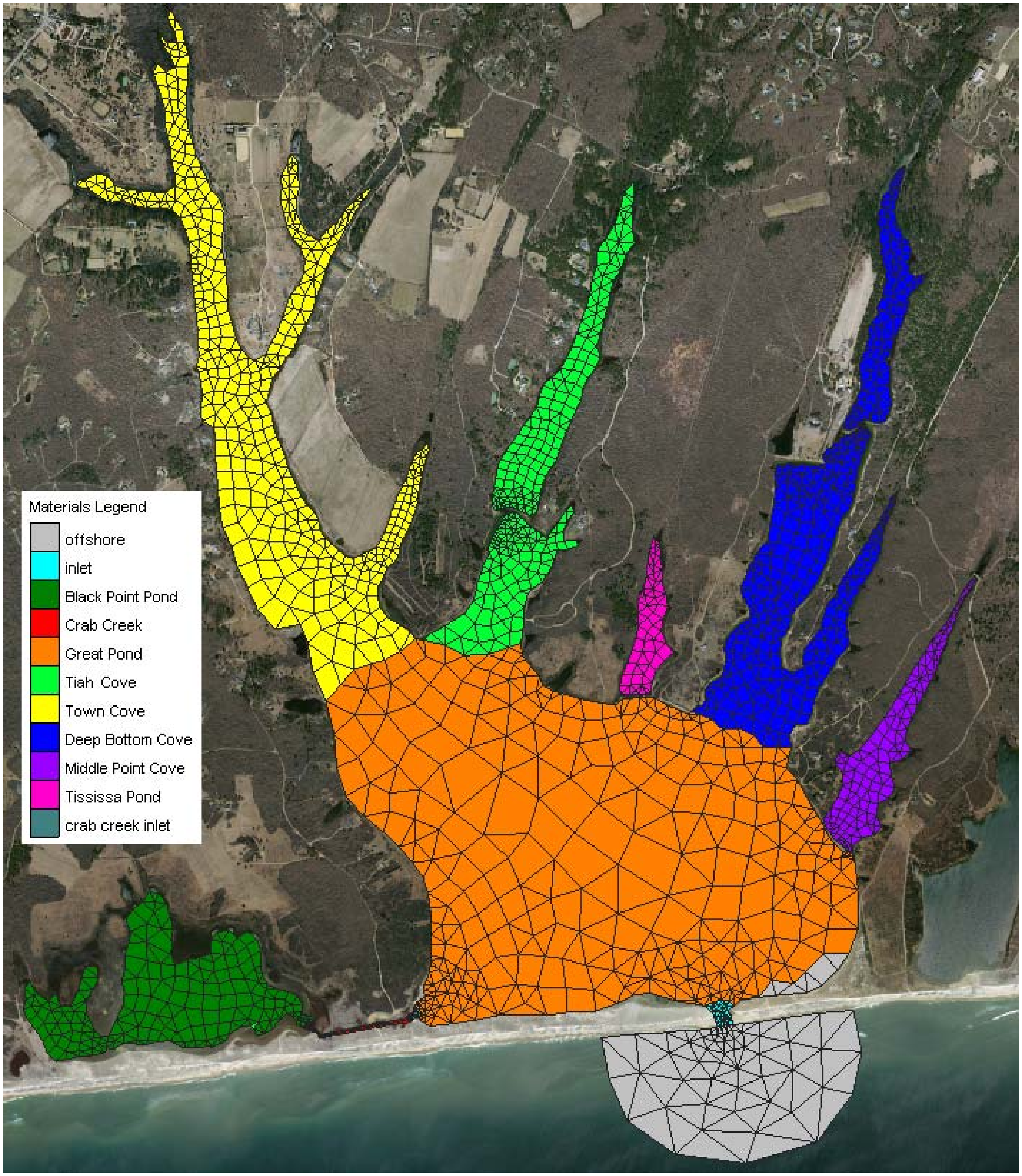

Figure V-10. Plot of hydrodynamic model grid mesh for Tisbury Great Pond. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

Calibration of the hydrodynamic model required a close match between the modeled and measured tides from stations inside the system (i.e., from the TDR deployments). Initially, the model was calibrated to obtain visual agreement between modeled and measured tides. Once visual agreement was achieved, a calibration the model was done based on dominant tidal constituents discussed in Section V-3.2. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents.

The calibrated model was used to analyze existing detailed flow patterns and compute residence times. The flushing analysis is based on the entire tidal record. 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 26-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.3.3.3.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 0.02 and 0.025 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. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based on ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992), and values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-5 for the different regions of the pond specified by the different grid material types of the numerical grid (Figure V-10).

V.3.3.3.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 5 and 50 lb-sec/ft^2 (Table V-5).

V.3.3.3.c Marsh porosity processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain included in the model of the Tisbury Great 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.

Table V-5. Manning's Roughness and eddy viscosity coefficients used in simulations of the Tisbury Great Pond system. These embayment delineations correspond to the material type areas shown in Figure V-10.

System Embayment	bottom friction	eddy viscosity lb-sec/ft^2
Offshore	0.025	50.0
Tisbury Great Pond Inlet	0.025	50.0
Black Point Pond	0.02	30.0
Crab Creek	0.02	30.0
Great Pond	0.025	50.0
Tiah Cove	0.025	50.0
Town Cove	0.025	50.0
Deep Bottom Cove	0.025	5.0
Tississa Pond	0.025	50.0
Crab Creek Inlet	0.02	50.0

V.3.3.3.d Comparison of modeled tides and measured tide data

A best-fit of model output for the measured data was achieved using the aforementioned values for friction and turbulent exchange. The model was first calibrated using the 8.5 day period beginning at 19:00 on April 4, which is during the period when Black Point Pond was tidally flushing. Figures V-11 through V-13 illustrate a comparison of the measured and modeled water levels in the system during the calibration time period. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the system embayments. The seven most prominent tidal constituents were selected for constituent comparison: the M_2, M_4, M_6, K_1, S_2, N_2, and O_1. Measured tidal constituent amplitudes compared with the final model constituent amplitudes are shown in Table V-6. The measured constituent amplitudes shown in this table differ from those in Table V-1 because only 7 constituents were computed for this analysis, while 22 constituents were calculated in Table V-2. Table V-7 shows error statistics for the final modeled results.

A second verification (corroboration) time period was used to further test the model. The model verification time period is 6.5 days long and starts at 21:30 on March 22, approximately 1 and one-half days after the breaching the inlet. During this period, Black Point Pond was not tidal, so the comparison of tide constituents cannot be performed. Computed constituents and error are presented in Table V-7 for the verification time period.

The constituent comparison resulted in a good agreement between modeled and measured tides. Most errors associated with tidal constituent amplitude 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 of the M_2 within the estuary were of the order of the tide gauge and model time step and small considering that the period of this tidal component is 12.42 hours long. This small error indicates a good agreement between the model and data.

A reasonable correlation (R^2) and low RMS error shown is in Table V-8 for all stations for both the calibration and verification time periods. Error statistics for both periods show a good correlation between the measured and modeled data, especially considering that the inlet is quasi-stable, unlike most other estuaries that have been modeled as a part of this project.

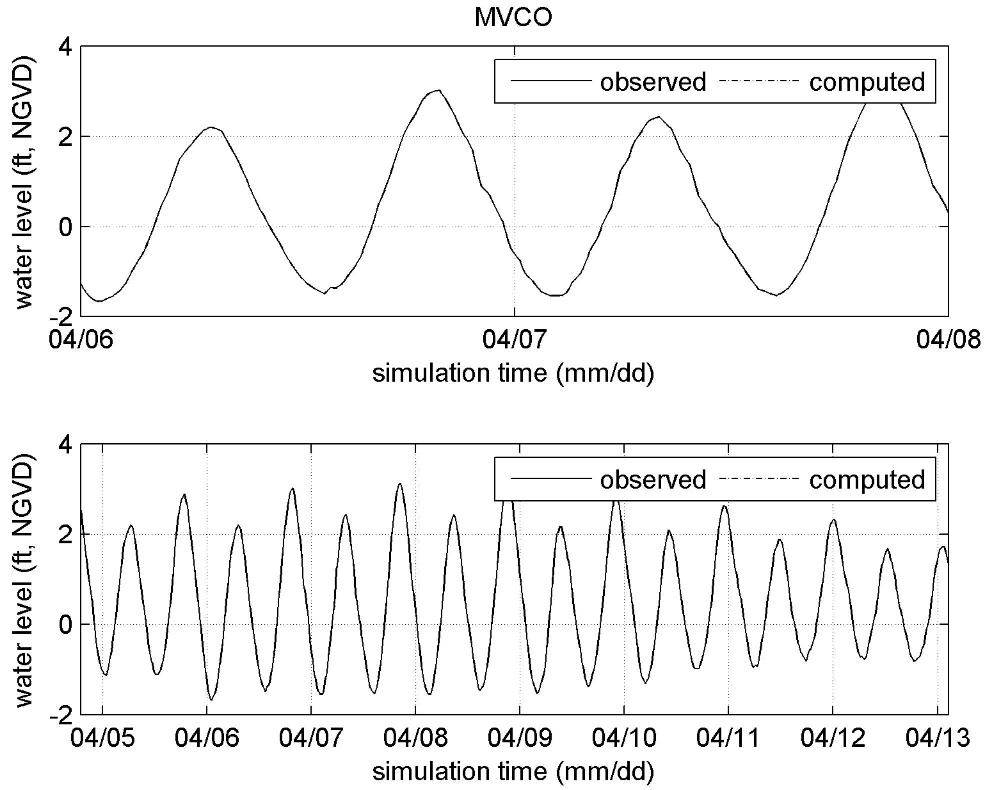

Figure V-11. Comparison of model output and measured tides for the MVCO station offshore for the final model run. The top plot is the sub-section of the longer segment of the total modeled time period shown in the bottom plot. The top plot shows the model during the time period when the inlet to the system was at its most stable (April 13 through April 20).

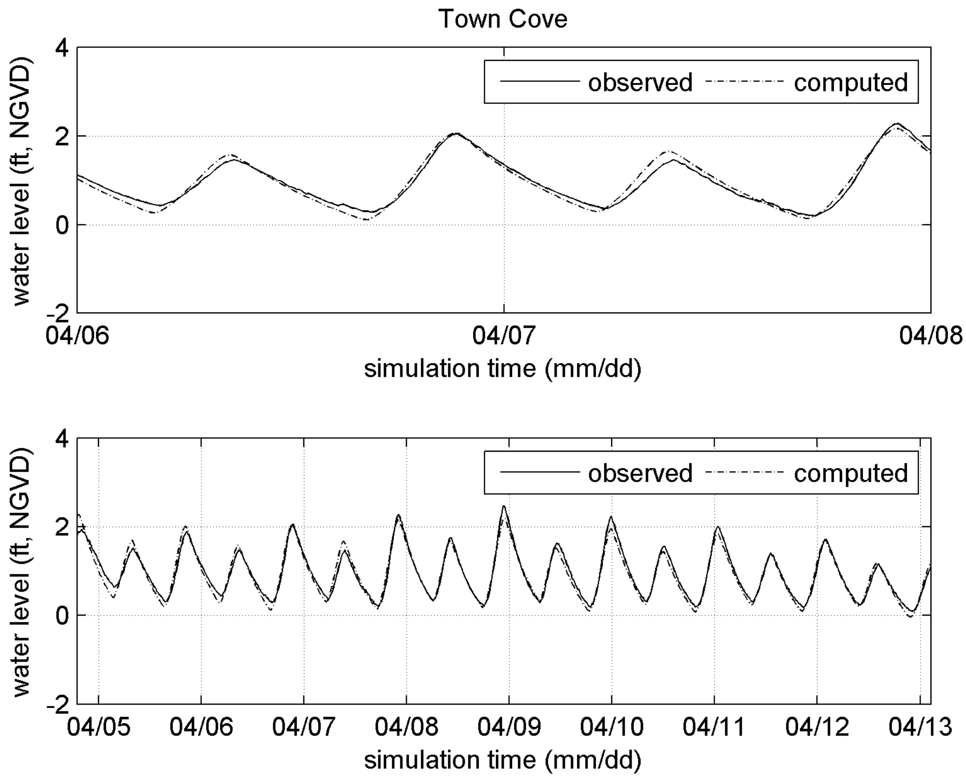

Figure V-12. Comparison of model output and measured tides for the Town Cove station for the final model run. The top plot is the sub-section of the longer segment of the total modeled time period shown in the bottom plot. The top plot shows the model during the time period when the inlet to the system was at its most stable (April 13 through April 20).

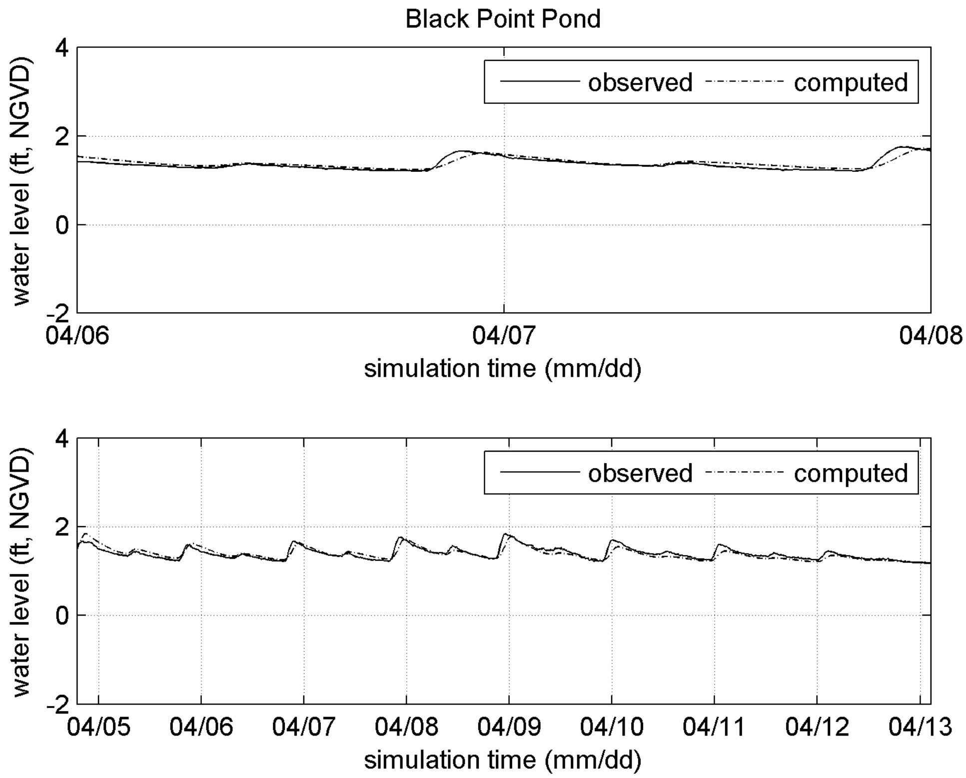

Figure V-13. Comparison of model output and measured tides for the Black Point Pond station for the final model run. The top plot is the sub-section of the longer segment of the total modeled time period shown in the bottom plot. The top plot shows the model during the time period when the inlet to the system was at its most stable (April 13 through April 20).

Table V-6. Tidal constituents for measured water level data and model output, with model error amplitudes, for Tisbury Great Pond during the model calibration period.

Location	Constituent Amplitude (ft)				Constituent Phase (degrees)
Modeled					
Location	M_2	M_4	M_6	K_1	M_2
MVCO offshore	1.77	0.15	0.05	0.26	-27.0
Town Cove	0.64	0.15	0.02	0.21	39.0
Black Point Pond	0.10	0.04	0.02	0.08	69.9
Measured					
	Constituent Amplitude (ft)				Constituent Phase (degrees)
Location	M_2	M_4	M_6	K_1	M_2
MVCO offshore	1.77	0.15	0.05	0.26	-27.0
Town Cove	0.67	0.15	0.02	0.19	33.7
Black Point Pond	0.09	0.03	0.01	0.08	96.7
Error					
	Error Amplitude (ft)				Error (minutes)
Location	M_2	M_4	M_6	K_1	M_2
MVCO offshore	0.00	0.00	0.00	0.00	0.1
Town Cove	-0.03	0.00	0.00	0.02	11.1
Black Point Pond	0.01	0.01	0.01	0.00	-55.5

Table V-7. Tidal constituents for measured water level data and model output, with model error amplitudes, for Tisbury Great Pond during the model verification period.

Location	Constituent Amplitude (ft)				Constituent Phase (degrees)
Modeled					
Location	M_2	M_4	M_6	K_1	M_2
MVCO offshore	1.17	0.10	0.04	0.21	-65.1
Town Cove	0.43	0.07	0.02	0.12	0.9
Measured					
	Constituent Amplitude (ft)				Constituent Phase (degrees)
Location	M_2	M_4	M_6	K_1	M_2
MVCO offshore	1.17	0.10	0.04	0.21	-65.3
Town Cove	0.49	0.08	0.02	0.14	-8.0
Error					
	Error Amplitude (ft)				Error (minutes)
Location	M_2	M_4	M_6	K_1	M_2
MVCO offshore	0.00	0.00	0.00	0.00	0.4
Town Cove	-0.06	-0.01	0.00	-0.02	18.4

Table V-8. Error statistics for the Tisbury Great Pond hydrodynamic model, for the full time series and the time period between April 13 and April 20.				
	Calibration time period		Verification time period	
	R^2	RMS error (ft)	R^2	RMS error (ft)
Offshore	1.00	0.00	1.00	0.06
Town Cove	0.95	0.11	0.92	0.11
Black Point Pond	0.65	0.08	-	-

As another example, from the calibrated mode of the Tisbury Great Pond system, the total flow rate of water flowing through the inlet culvert can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-14. During spring tides, the maximum flood flow rates reach 5000 ft^3/sec at Tisbury Great Pond inlet.

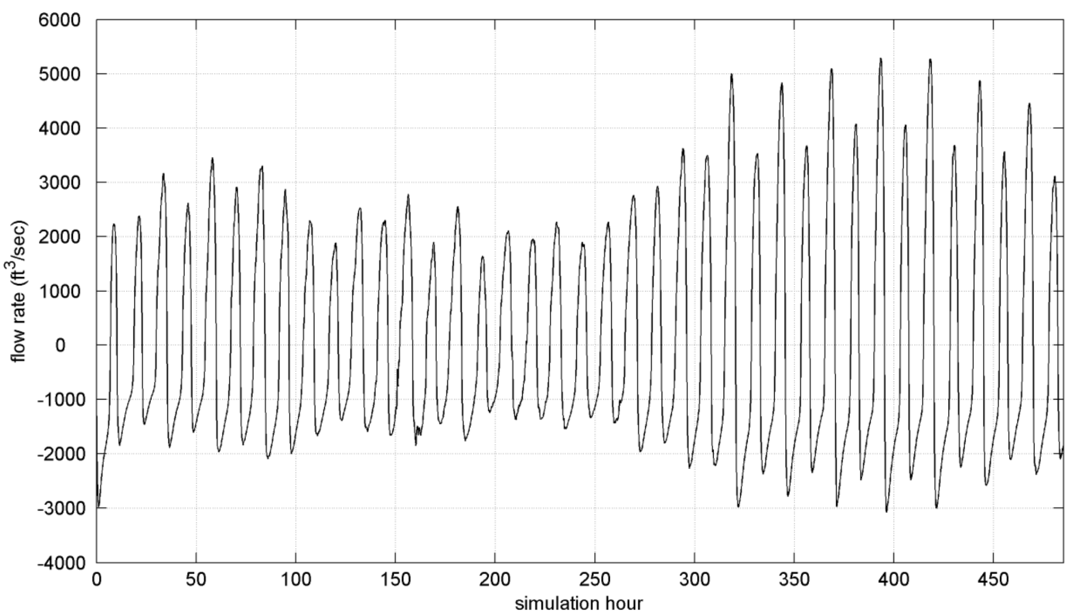

Figure V-14. Time variation of computed flow rates at the Tisbury Great Pond inlet. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flow indicated flooding tide flows, while negative flow indicates ebbing tide flows.

V.3.4 Flushing Characteristics

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through the inlet, the primary mechanism controlling estuarine water quality within the modeled Tisbury Great Pond system is tidal exchange. A rising tide offshore creates a slope in water surface from the ocean into the upper-most reaches of the modeled system. Consequently, water flows into (floods) the system. Similarly, the estuary drains into the open waters of the ocean on an ebbing tide. This exchange of water between the system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of the harbor system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

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

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

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

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

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

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

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

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

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

Residence times were calculated as the volume of water (based on the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Model divisions used to define the system sub-embayments include 1) the entire Tisbury Great Pond system, 2) Black Point Pond, 3) Town Cove, 4) Tiah Cove and 5) Deep Bottom Cove. These system divisions follow the model material type areas designated in Figure V-10. Sub-embayment mean volumes and tide prisms are presented in Table V-9.

Table V-9. Embayment mean volumes and average tidal prism for the Tisbury Great Pond System.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Tisbury Great Pond System	169,958,000	37,800,000
Black Point Pond	7,889,000	574,000
Town Cove	25,764,000	7,616,000
Tiah Cove	8,311,000	2,807,000
Deep Bottom Cove	16,397,000	4,855,000

Residence times were averaged for the tidal cycles comprising a representative 25 day period (48 tide cycles) using the calibrated model and water level data from the MVCO offshore boundary condition, and are listed in Table V-10. The flushing rates for Black Point Pond were calculated using a shorter period of time when the pond water levels were tidal after April 4. The modeled time period used to compute the flushing rates consists of the entire length of tidally dominated data available, this period excludes the initial system draining time corresponding with the creation of the inlet. The RMA-2 model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume. Since the period used to compute the flushing rates of the system represent average tidal conditions when the inlet is open, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments after a successful breach.

A flushing time of 2.3 days for the entire estuary shows that on average, water is resident in the system for less than days. This modest residence time provides some confidence that the temporary channel allows enough exchange to significantly improve water quality during a typical breach event. System sub-embayments typically have local flushing times that are equal to or less than 2.3 days. Tiah Cove has the shortest local flushing time, because this embayment has a smaller mean sub-embayment volume, relative to its tide prism. This indicates that even though the pond has a greatly restricted tide range, with a residence time of 1.5 days, it flushes extremely well. Black Point Pond has a local residence time of over 7 days when it is tidally flushing, indicating that it does not flush well. Furthermore the very long system residence time of Black Point Pond indicates that this sub-embayment may be more sensitive to nutrient loading than other sub-embayments within the system.

Table V-10. Computed System and Local residence times for embayments in the Tisbury Great Pond system.

Embayment	System Residence Time (days)	Local Residence Time (days)
Tisbury Great Pond System	2.3	2.3
Black Point Pond	153.3	7.1
Town Cove	11.6	1.8
Tiah Cove	31.3	1.5
Deep Bottom Cove	18.1	1.8

The local residence times in all areas of the Tisbury Great Pond system show that they would likely have good water quality if the system water with which it exchanges also has good water quality. For example, the water quality of Town Cove would likely be good as long as the water quality of the Great Pond was also good. Furthermore a successful breach would likely remain open to tidal flushing for longer than the residence times of most of the system. This indicates that a successful breach would do much to improve water quality within the system. Actual water quality would still also depend upon the total nutrient load to each embayment and the length of time that the inlet allows tidal exchange between the ocean and the system.

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

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

VI. WATER QUALITY MODELING

The water quality modeling analysis approach that has been typically used for other systems that have been studied as part of the Massachusetts Estuaries Project was slightly modified for Tisbury Great Pond. This modified approach has been applied to other estuary systems that are periodically breached, like Edgartown Great Pond, also located on the south shore of the Vineyard, and Sesechacha Pond, on the eastern shore of Nantucket.

This system differs from most other systems modeled as part of the MEP because it does not have inlet that is open at all times to the ocean. Water quality in the Pond is managed presently by periodically opening an inlet to the ocean. For past breaches, the length of time that the inlet remains open after it is breached varies between 1 and 24 weeks, based on observations of openings made from 1995 through 2012. On average, the pond is open 144 days total a year, which means it is closed off from the ocean 60% of the time.

Because Tisbury Great Pond is actively managed in such a fashion, the water quality analysis has to include methods for determining conditions in the Pond at times when it is both open and closed to tidal exchange with the ocean. During times when the Pond inlet is breached, the RMA-4 model was used to model water quality constituent dispersion throughout the Pond's main basin and the series of coves. During the long periods when the breach is closed, a simple mass balance model was developed. As used together in this analysis, these two modeling techniques accurately simulate conditions in the Pond throughout the critical summer months, and provide a method of investigating alternatives to manage pond health.

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort for the Tisbury Great 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 salinity and nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Field measurements and hydrodynamic modeling of the embayment provide essential preparatory input to the water quality model development effort. The pond breach simulation discussed in Chapter V is an important tool for determining the water quality dynamics that are in effect presently, and also for investigating how possibly the pond could be managed differently in the future to further improve water quality conditions. 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. For each of the modeling scenarios presented in this chapter, the breach model was run using tide data record measured offshore of Katama Beach, at the Martha's Vineyard Coastal Observatory (MVCO). These tide data were used as boundary condition used to force the RMA-2 model of Great Pond.

VI.1.2 Nitrogen Loading to the Embayments

Three primary nitrogen loads to Tisbury Great Pond are included in this modeling study: external loads from the watersheds, nitrogen load from direct rainfall on the embayment surface, and internal loads from the sediments. In addition to these three nitrogen loads to the pond, the

Atlantic Ocean is a background source of nitrogen that is important to include in the model when simulating periods when the pond inlet is open and flushing. This load is represented as a constant concentration along the seaward boundary of the RMA-4 model grid during the pond breach simulation period.

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates salinity and total nitrogen concentrations in Great Pond in response to the existing flushing conditions and loadings, it was necessary to calibrate the model to actual measurements. The refined and approved data for the 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. For Tisbury Great Pond, a maximum of 12 years of salinity and TN measurements are available from the years 1995 through 2007 and 2011.

Table VI-1. Measured nitrogen concentrations and salinities for Tisbury Great Pond. "Data mean" values are calculated as the average of the separate yearly means. TN data represented in this table were collected from 1995 through 2007 and 2011 in Great Pond. The offshore Atlantic Ocean data (offshore Pleasant Bay Inlet) are from the summer of 2005.

Sampling Station Location	Station ID	Years of Data	total nitrogen			salinity		
			data mean (mg/L)	s.d. all data (mg/L)	N	data mean (ppt)	s.d. all data (ppt)	N
Town Cove upper	TGP-1	12	0.643	0.254	48	9.9	7.1	50
Tiasquam River	TGP-2	11	0.563	0.219	42	10.5	6.9	44
Pear Tree Cove	TGP3	6	0.485	0.132	23	12.6	6.8	24
Muddy Cove	TGP-3A	1	0.785	0.422	4	14.7	4.4	4
Town Cove Mid	TGP-4	12	0.528	0.197	68	14.7	7.7	71
Tiah Cove	TGP-5	3	0.422	0.134	21	12.0	4.3	21
Deep Bottom Cove	TGP-6	12	0.536	0.213	49	14.3	5.8	53
Tisbury Great Pond low	TGP-7	11	0.509	0.263	49	17.0	6.3	53
Crab Creek	TGP-8	3	0.430	0.124	13	13.1	4.1	13
Tisbury Great Pond mid	TGP-9	1	0.413	0.156	4	13.2	5.7	4
Atlantic Ocean			0.232	0.044	17	32.3	0.6	5

VI.2 MODEL DESCRIPTION AND APPLICATION

The overall approach used in the analysis of Tisbury Great Pond involves first developing a salinity model of the Pond. Salinity is a conservative water quality constituent, meaning that is has no active sources or sinks other than tidal exchange with the ocean. Because salinity data are conservative, they are excellent calibration data for systems such as Great Pond. In such simple systems it is an easy task to compute water recharge and rainfall rates based on the observed salinity record.

The Great Pond analysis requires that both periods when the inlet is open and closed be considered, so a two-part approach was developed. The initial period (when the Pond inlet is breached in the early summer and there is tidal exchange with the ocean) is modeled using the RMA-4 dispersion model. The following period when the inlet is closed, and the Pond behaves like a simple reservoir, is also simulated using the RMA-4 and also includes fresh water inputs and constituent mass flux into the Pond (which is 0 for the salinity simulation) throughout the simulation period.

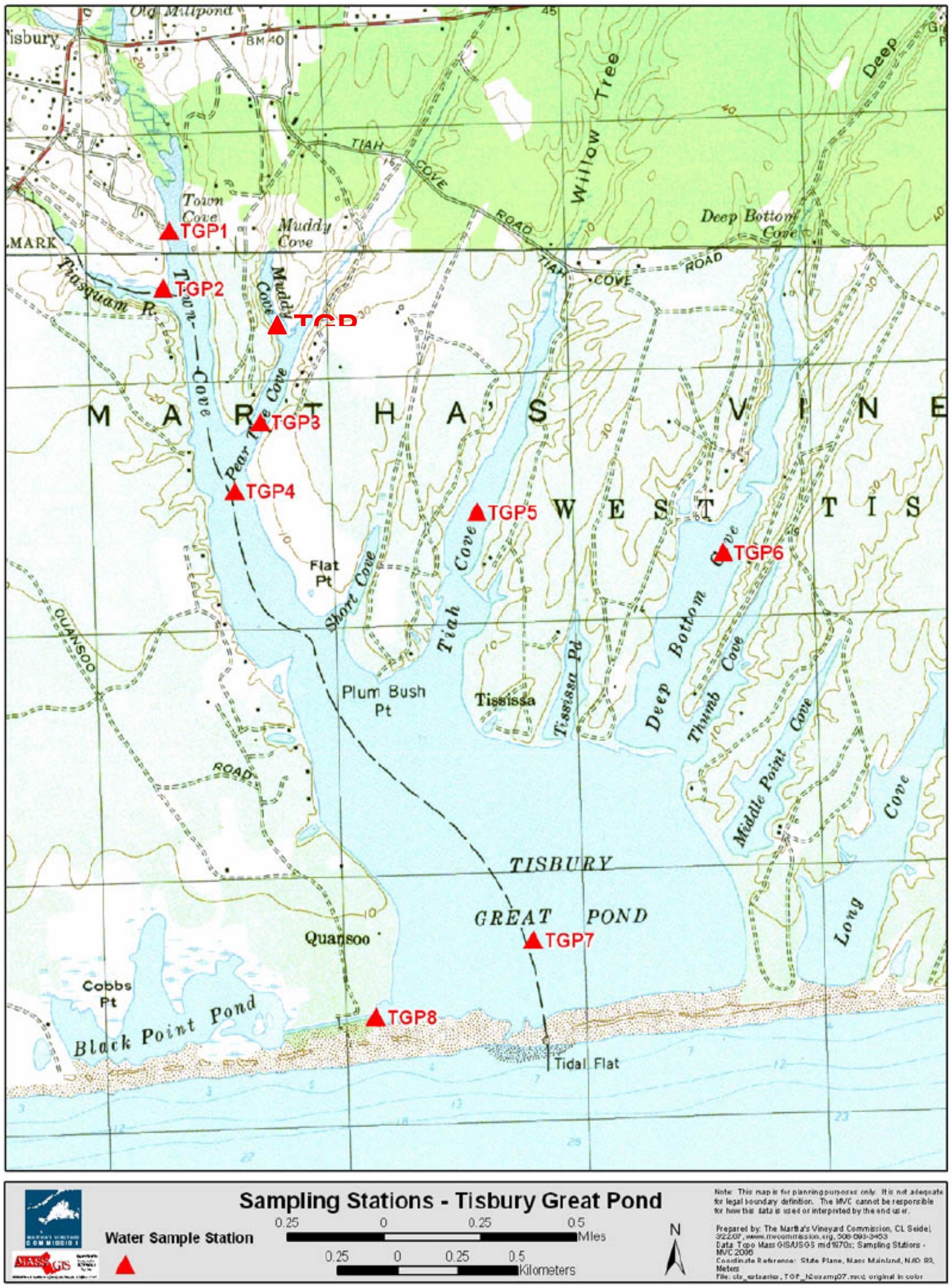

Figure VI-1. USGS topographic map showing monitoring station locations in Tisbury Great Pond that were used in the water quality analysis.

With a calibrated salinity model, a verification of the model is performed using total nitrogen, which is as a non-conservative constituent. For TN, bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. The TN model considers summertime loading 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 Martha's Vineyard 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.

VI.2.1 Model Formulation

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of water quality constituent dispersion in Great Pond during the periods when it is open and also closed to the ocean and tidal flushing. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of the 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. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod embayments, including systems other Massachusetts estuarine systems such as Pleasant Bay (Howes *et al*., 2006); Falmouth (Howes *et al*., 2005); and Mashpee, MA (Howes *et al*., 2004), and including other periodically breached coastal ponds like Sesechacha Pond on Nantucket Island (Howes *et al*., 2006).

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_o and D_{ee} 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 time varying salinity and total nitrogen concentrations throughout Pond through the course of a month-long inlet opening.

VI.2.2 Boundary Condition Specification

Mass loading of nitrogen into the model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed, direct atmospheric deposition and benthic flux loads for the whole Pond were evenly distributed across the cells that make up the RMA computational grid.

The loadings used to model present conditions in Tisbury Great Pond 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, resulting in a total flux for the 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. Sediments in the northern basin of the Pond tend to have negative fluxes, which indicates that they are a nitrogen sink. The N production of the bottom sediment in other areas is greater than this sink, and as a result, the net flux from the whole pond is positive.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified for the dispersion model for the simulation of periods when the inlet is open. The model uses concentrations at the open boundary during the flooding tide periods of the RMA-4 model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The TN boundary concentration in the Atlantic Ocean region offshore the Pond was set at 0.232 mg/L, based on SMAST data collected offshore Pleasant Bay in the summer of 2005. For the salinity model, the offshore concentration was set at 32.3 ppt.

Table VI-2. Present conditions sub-embayment and surface water loads used for total nitrogen modeling of Tisbury Great Pond, 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)
Deep Bottom Cove	2.803	1.507	0.550
Tiahs Cove	2.247	0.775	-1.338
Pear Tree Cove	3.836	0.258	0.007
Tisbury Great Pond main basin	22.096	7.830	9.594
Black Point Pond	0.800	0.926	6.170
Mill Brook (freshwater)	8.644	-	-
Tiasquam River (freshwater)	5.556	-	-
Total	45.98	11.296	14.982

VI.2.3 Development of Present Conditions Model

To simulate present water quality conditions in Great Pond, separate RMA-4 models were developed to represent conditions in the Pond when the inlet is open and the pond is tidally flushing and also for periods when the inlet is closed.

For time periods when the pond was closed off from the ocean, a RMA model that has no open ocean boundary condition was developed and calibrated. This model requires an initial salinity and pond water level, as well as a fresh water flux into the pond (groundwater and surface water discharge) and pond water discharge thorough the barrier beach. The closed pond model was calibrated using data from summer 2006, which is a period where good-quality contemporaneous TN, salinity, and pond elevation data exist. The initial salinity (16.2 ppt) was measured on August 3. The initial Pond elevation was set at 3.1 feet NAVD based on measurements of the pond published by Healey (2009). The net freshwater input (groundwater and streams) to the model is 33.1 ft^3/sec. In order to achieve the water level increase (0.4 feet) observed between August 3 and 21 during the modeled time period, an input of only 8.1 ft^3/sec is required. This indicates that the pond discharge through the barrier beach is 25.0 ft^3/sec. The rate of flow through the barrier beach varies with the water level of the Pond. With lower elevations, the flow-through is less, and pond levels increase at a greater rate. For example, between July 29 and August 25, 2003 the measured water level rose from 1.0 feet NAVD to 2.8 feet NAVD, which requires a discharge through the barrier beach of only 7.8 ft^3/sec.

The model was calibrated by only changing the values of the diffusion coefficient applied to the different areas of the modeled domain. Diffusion coefficient values determined during the model calibration process are listed in Table V-3 for the sub-divisions of the Pond. The final calibrated model raises the water level in the pond by the required 0.4 feet measured between August 3 and 2, while salinities lower across the pond. A plot of model output versus measured salinities at the two monitoring stations (TGP4 and TGP7) used for the calibration is presented in Figure VI-2, for the start and end of the 17-day simulation. The modeled and measured data show good agreement, with a RMS error of 0.7 ppt and a R^2 correlation of 0.93. A contour plot of salinity contours in the Pond at the end of the simulation is presented in Figure VI-3.

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

Embayment Division	E m^2/sec
Deep Bottom Cove	10.0
Tiah Cove	10.0
Pear Tree Cove	10.0
Tisbury Great Pond main basin	5.0
Tisbury Great Pond upper basin	2.0
Town Cove	1.0
Black Point Pond	10.0
Mill Brook inlet	2.0
Tiasquam River inlet	2.0

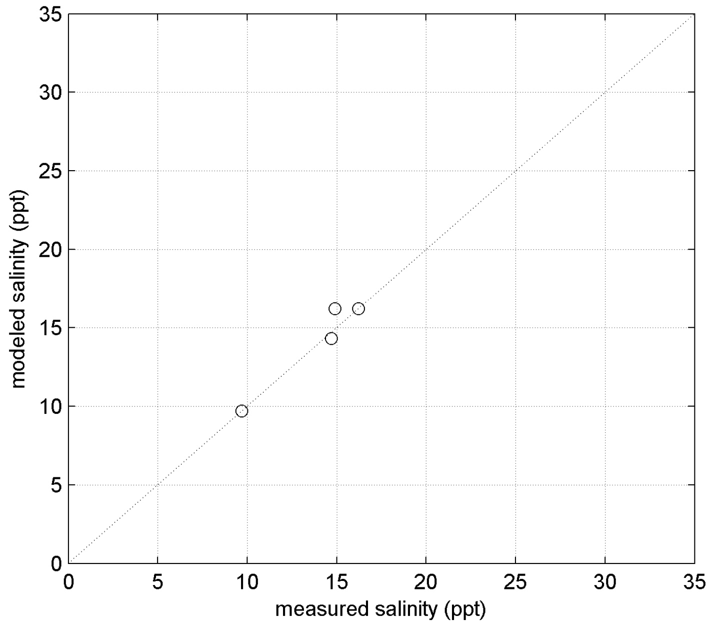

Figure VI-2. Model salinity target values are plotted against measured data, together with the unity line, for the simulation period from August 3 through 21, 2006. RMS error for this model verification run is 0.7 ppt and the R^2 correlation coefficient is 0.93.

By opening the calibrated salinity model to ocean tides, the behavior of the system when it is tidally flushing can be simulated. Figure VI-4 shows traces of salinity at monitoring station TGP7 for three initial conditions for the pond: 20 ppt 15 ppt and 10 ppt. These simulations were all run with the same open ocean tidal boundary condition developed from measured MVCO tide data, as discussed in Chapter V. The plot of salinities in the main basin of the Pond show that after 14 days of tidal flushing, the salinities are close to being equal. This indicates that with optimal tidal flushing conditions (i.e., with the formation of a stable inlet), the pond can be well flushed after 2 weeks from most any starting condition in the Pond. The actual stability (as effected by storms and waves) of an inlet cut would of course control the rate of water quality improvements.

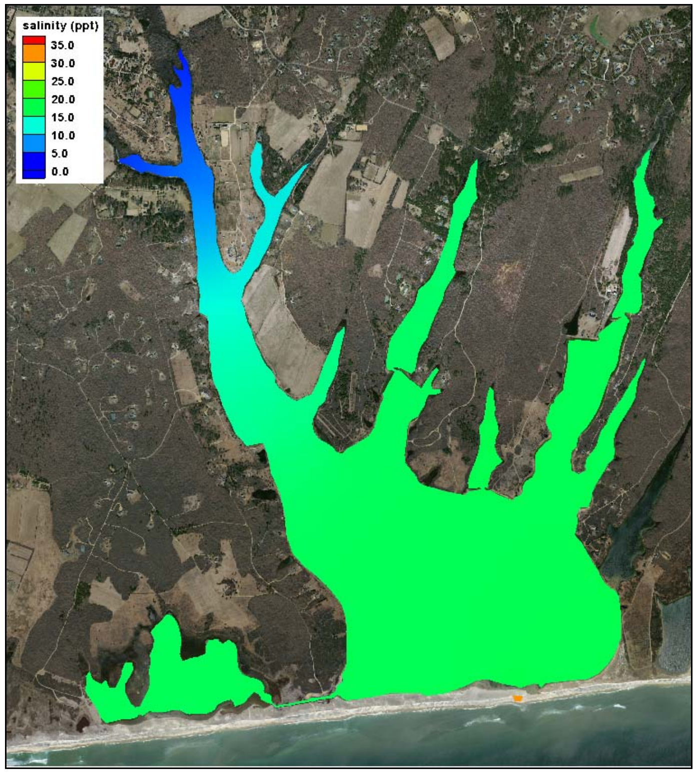

Figure VI-3. Plot of salinity contours in Tisbury Great Pond and Black Point Pond at the end of the modeled August 2006 calibration period.

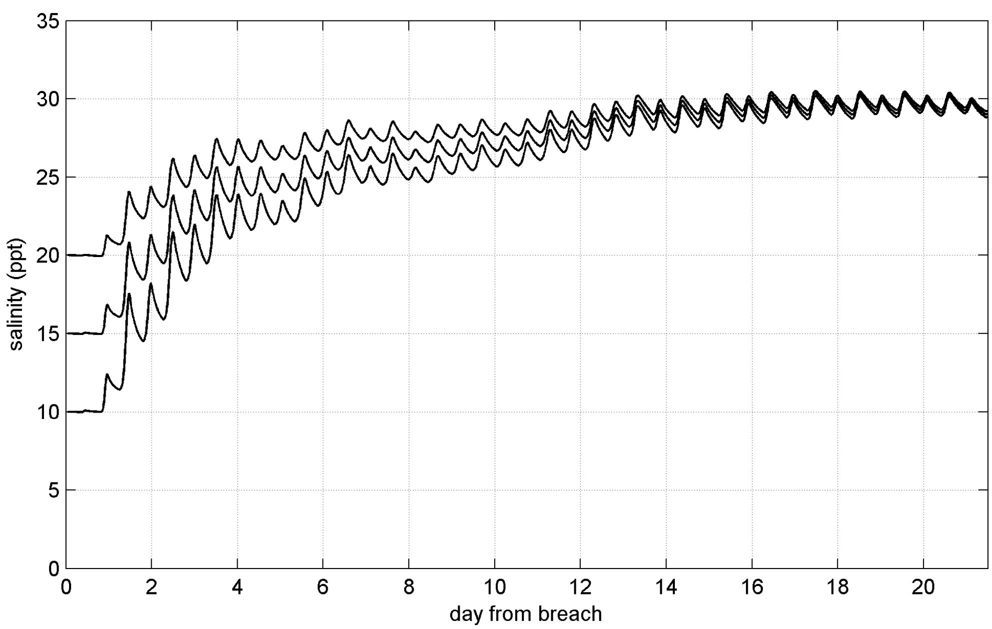

Figure VI-4. RMA-4 model output for Tisbury Great Pond showing how pond salinities vary as a function of initial salinity concentration (here for 10, 15 and 20 ppt) and number of days open for the breach. Model output is taken at monitoring station TGP7. Model results also assume a fully open breach for the complete simulation period.

VI.2.4 Total Nitrogen Model Development

With the diffusion coefficients determined from the salinity model calibration, the TN model of Tisbury Great Pond was developed using the watershed and atmospheric loads presented in Table V-2. Benthic loads were computed based on the spatial distribution of the cores sampled for this study. In the model calibration period between August 3 and 21, 2006 TN concentrations rose from 0.37 mg/L to 0.47 mg/L in the main basin of the pond. Initial TN concentrations at the start of the simulation were set in the pond using the measured TN data from August 3. This established the gradient of TN concentrations across the pond that existed at the beginning of the simulation period.

Using the initial TN concentrations gradient, nitrogen sources from Table VI-2, and diffusion coefficients from Table VI-3, the model is able to accurately simulate this rise in the main basin and in Town Cove. In the model TN rises from 0.370 mg/L to 0.486 mg/L at station TGP7 in the main basin, and from 0.465 mg/L to 0.535 mg/L at station TGP4 in Town Cove, near the inlet of Pear Tree Cove. Model output plotted versus measured data presented in Figure VI-5 show that the TN model represents well the rise of TN concentrations in the Pond during the simulation period, with a RMS error of 0.010 mg/L and an R^2 of 0.97. Contours of TN concentrations across the Pond at the end of the 21-day simulation are presented in Figure VI-6.

Similar to the salinity model, the calibrated model was opened to tidal flushing to simulate how TN concentrations change when the system is breached. Three initial conditions where modeled: 0.8 mg/L, 0.6 mg/L and 0.4 mg/L. Similar to the salinity model results, after day 14 of the model run, TN concentrations are essentially the same for the three scenarios. This corroborates that results of the salinity model, that suggest that 14 days is an adequate period to bring the pond to a state of tidal equilibrium.

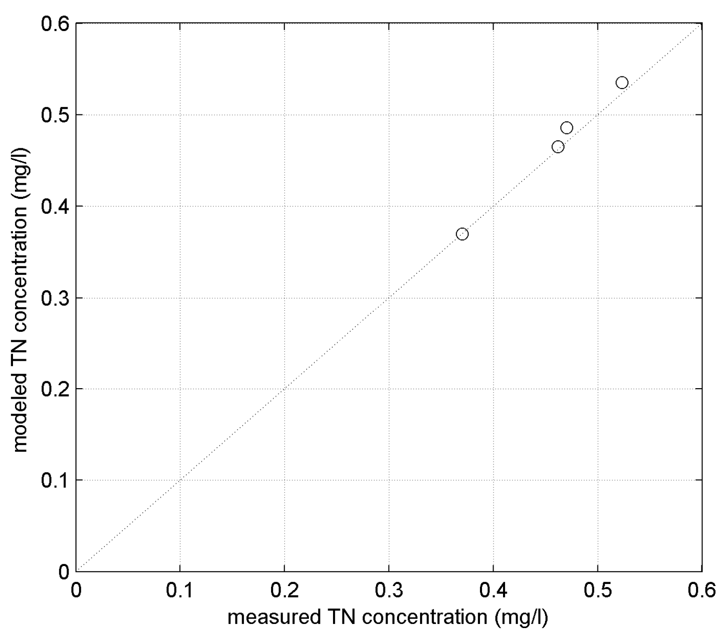

Figure VI-5. Model TN target values are plotted against measured concentrations, together with the unity line, for the simulation period from August 3 through 21, 2006. RMS error for this model verification run is 0.010 mg/L and the R^2 correlation coefficient is 0.97.

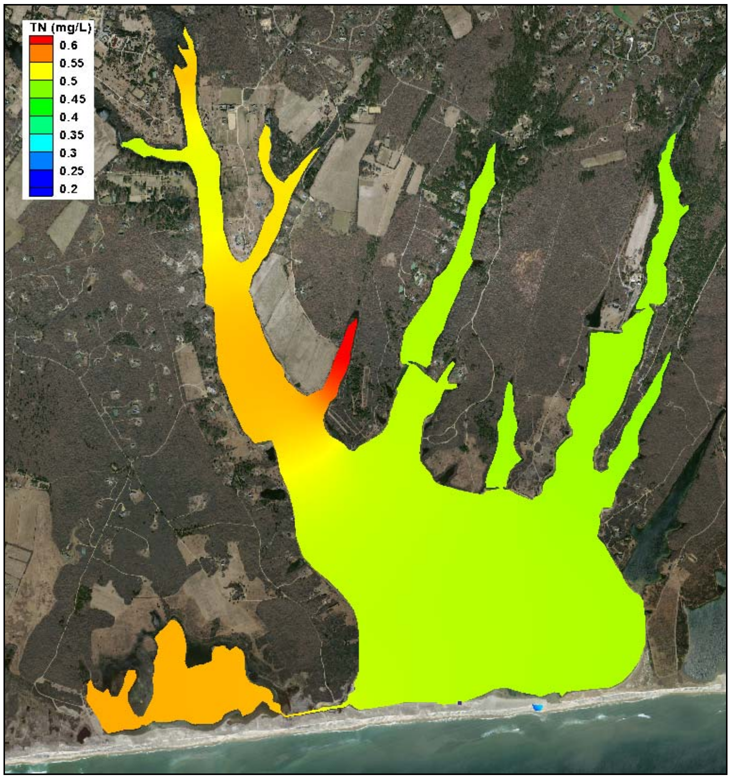

Figure VI-6. Plot of TN contours in Tisbury Great Pond and Black Point Pond at the end of the modeled August 2006 calibration period.

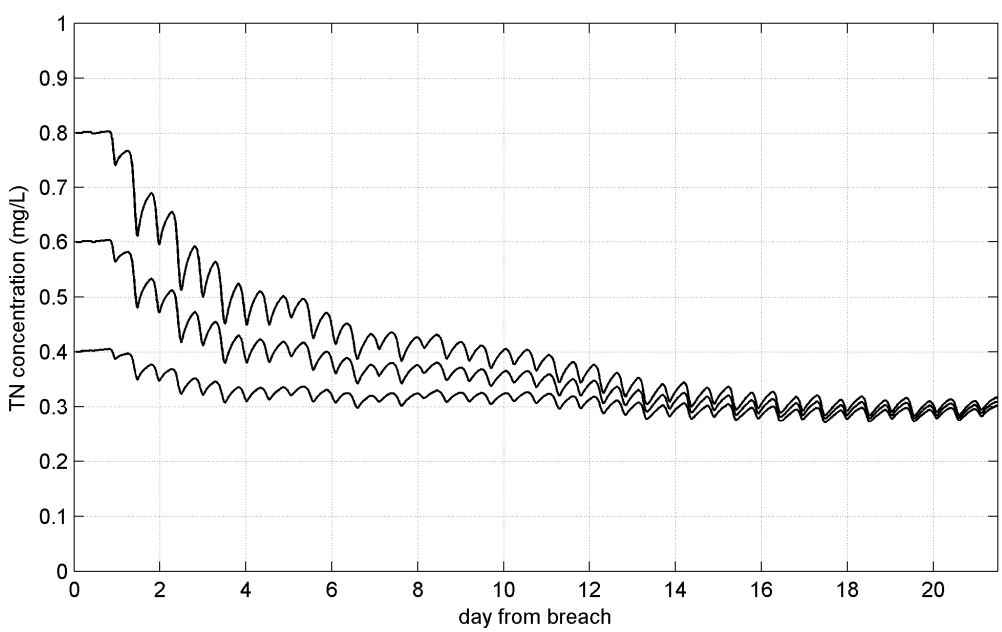

Figure VI-7. RMA-4 model output for Tisbury Great Pond showing how pond TN concentrations vary as a function of initial salinity concentration (here for 10, 15 and 20 ppt) and number of days open for the breach. Model output is taken at monitoring station TGP7. Model results also assume a fully open breach for the complete simulation period.

VI.2.5 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations in Great Pond, the standard "build-out" and "no-load" water quality modeling scenarios were run. These runs included two "build-out" scenarios, 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. 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. The changes in watershed loads compared to present conditions are presented in Table VI-4.

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present (2003), present 2007, build-out, and no-anthropogenic ("no-load") loading scenarios of Edgartown Great Pond. 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
Deep Bottom Cove	2.803	4.597	+64.0%	1.003	-64.2%
Tiahs Cove	2.247	2.540	+13.0%	0.685	-69.5%
Pear Tree Cove	3.836	3.942	+2.8%	1.504	-60.8%
Tisbury Great Pond main basin	22.096	22.901	+3.6%	13.079	-40.8%
Black Point Pond	0.800	1.482	+85.3%	0.260	-67.5%
Mill Brook (freshwater)	8.644	9.397	+8.7%	5.814	-32.7%
Tiasquam River (freshwater)	5.556	8.085	+45.5%	1.874	-66.3%
Total	45.981	52.945	+15.1%	24.219	-47.3%

VI.2.5.1 Build-Out

A breakdown of the total nitrogen load entering the Pond for the modeled build out scenario is shown in Table VI-5. A simulation of Tisbury Great Pond with build out loading during closed hydrodynamic conditions was run to compare with present conditions watershed loading. The simulation was run for 60 days, with an initial pond concentration of 0.30 mg/L, which is typically within the range of the lowest TN values in the measured data record, and likely represents the optimum TN value for a successful inlet breaching. Because the watershed load increases by only 15%, the increase in TN concentrations is moderate for build out loading. TN concentrations at station TGP7 increase from 0.673 mg/L with present conditions to 0.729 mg/L for build out at the end of the 60-day simulation period, as is seen in the results plotted in Figure VI-8.

Table VI-5. Build out scenario sub-embayment and surface water loads used for total nitrogen modeling of Tisbury Great Pond, 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)
Deep Bottom Cove	4.597	1.507	0.992
Tiahs Cove	2.540	0.775	-1.408
Pear Tree Cove	3.942	0.258	0.007
Tisbury Great Pond main basin	22.901	7.830	10.180
Black Point Pond	1.482	0.926	6.430
Mill Brook (freshwater)	9.397	-	-
Tiasquam River (freshwater)	8.085	-	-
Total	52.945	11.296	16.201

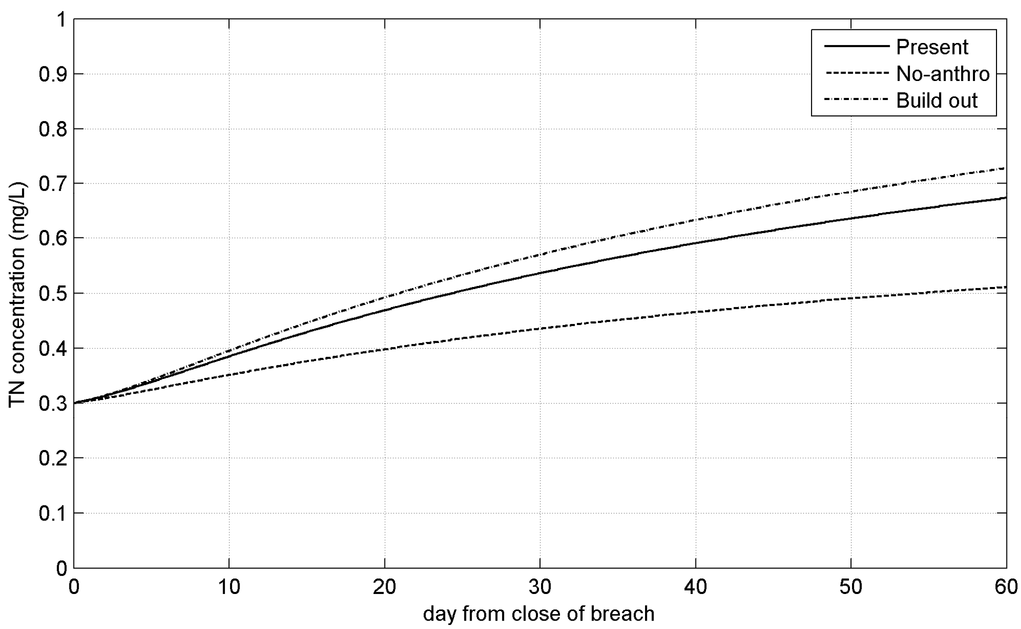

Figure VI-8. Comparison of modeled TN concentrations in the main basin of Tisbury Great Pond (at monitoring stations TGP7) during closed (non-tidal) hydrodynamic conditions. Plotted results show present watershed loading, no-anthropogenic and build out loading conditions over the 60-day simulation period.

VI.2.5.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering the Pond for the modeled Build-out scenario is presented in Table VI-6. Similar to what done for build out conditions, a simulation of Tisbury Great Pond with “no-load” loading during closed hydrodynamic conditions was run to compare with present conditions watershed loading. The simulation was run for 60 days, with an initial pond concentration of 0.30 mg/L, which is typically within the range of the lowest TN values in the measured data record, and likely represents the optimum TN value for a successful inlet breaching. There is a large reduction in watershed load for the “no-load” scenario, which results in a similar drop in TN concentrations compared to present conditions.

At the end of the 60-day simulation period, TN concentrations rise to only 0.511 mg/L (Figure VI-8) in the main basin of the Pond with the "no-load" scenario, which is 0.162 mg/L less than for present conditions loading at this same monitoring station. This represents a 37% decrease in TN concentrations (compared to the background ocean TN concentration of 0.232 mg/L).

Table VI-6. No-anthropogenic ("no-load") scenario sub-embayment and surface water loads used for total nitrogen modeling of Tisbury Great Pond, 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)
Deep Bottom Cove	1.003	1.507	-0.414
Tiahs Cove	0.685	0.775	-1.099
Pear Tree Cove	1.504	0.258	0.007
Tisbury Great Pond main basin	13.079	7.830	7.871
Black Point Pond	0.260	0.926	5.354
Mill Brook (freshwater)	5.814	-	-
Tiasquam River (freshwater)	1.874	-	-
Total	24.219	11.296	11.718

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Tisbury Great Pond Embayment System in the Towns of Chilmark and West Tisbury, MA, our assessment is based upon data from the water quality monitoring program developed by the Towns and the Martha's Vineyard Commission, with technical assistance from SMAST, as well as field survey and historical data collected under the programmatic umbrella of the Massachusetts Estuaries Project. These data include temporal surveys of eelgrass distribution; surveys of benthic animal communities and sediment characteristics; and time-series measurements of dissolved oxygen and chlorophyll-*a* during the summer and fall of 2005. 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 (Section VIII). Part of the MEP assessment necessarily includes confirmation that the critical nutrient for management in any embayment is nitrogen and determination that a system is or is not impaired by nitrogen enrichment. Analysis of inorganic N/P molar ratios within the watercolumn of the Tisbury Great Pond Embayment System support the contention that nitrogen is the nutrient to be managed, as the Redfield Ratio (inorganic N/P) ranges from 2-7 within the main basin and coves of Tisbury Great Pond and 6 within Black Point Pond. These data indicate that nitrogen additions will increase phytoplankton production, organic matter levels and turbidity within this system. Increased phytoplankton and organic matter levels increase oxygen consumption within the waters and sediments and increase the extent of oxygen depletion and habitat impairment. It should be noted that nitrogen enrichment occurs through two primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with low nitrogen offshore waters. Tisbury Great Pond has seen increasing nitrogen loading from its watershed from shifting land-uses and due to coastal processes along its barrier beach which is only periodically opened to 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 stable. The concept is to use species, which integrate environmental conditions over seasonal to annual intervals. The approach is particularly useful in environments where high-frequency variations in structuring parameters (e.g. light, nutrients, dissolved oxygen, etc.) are common, making adequate field sampling difficult.

As a basis for a nitrogen threshold determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll-*a* (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed autonomously recording dissolved oxygen sensors throughout Tisbury Great Pond at critical points in the system. The sensors were sited such that they would be representative of dissolved oxygen conditions within major sub-basins comprising the Tisbury Great Pond Estuary, namely Town Cove, Tiah Cove, Deep Bottom/Thumb Cove and the main basin of Tisbury Great Pond (west end and southeast corner). The six dissolved oxygen moorings were deployed to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Tisbury Great Pond system was limited as little information on eelgrass distribution exists from previous studies by the Martha's Vineyard Commission and the MassDEP Eelgrass Mapping Program (C. Costello) relied on aerial photo analysis. MEP Technical staff did interview various persons knowledgeable about Tisbury Great Pond and conducted a general survey as part of the mooring program (2005 & 2007) and sediment and infauna surveys in 2005. It should be noted that MEP staff did not observe any eelgrass in the pond as it was completing its data collection tasks. Temporal trends in the distribution of eelgrass beds are typically used by the MEP to assess the stability of the habitat and to determine trends potentially related to nutrient enrichment and water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. This is consistent with results from the Water Quality Monitoring Program indicating that phytoplankton production (blooms) within the basins of the Tisbury Great Pond Estuary are prevalent and are enhanced by nitrogen. This is based upon inorganic nitrogen to phosphorus ratios, where system wide the basin averages range from 2-7. While this ratio approach (Redfield Ratio) is an approximation, where values <16 indicate nitrogen limitation, >16 phosphorus limitation, the low value of the ratio provides additional site-specific evidence that nitrogen is the appropriate nutrient for management of eutrophication in this system.

While a temporal change in eelgrass distribution provides a basis for evaluating increases (nitrogen loading) or decreases (increased flushing- change in breaching schedule) in nutrient enrichment within the Tisbury Great Pond System, some areas have not historically and do not presently support eelgrass. In these areas, benthic animal indicators were used to assess the level of habitat health from “healthy” (low organic matter loading, high D.O.) to “highly stressed” (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of their habitat. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life-history information on the species and a wide variety of field studies within southeastern Massachusetts waters, including the Wild Harbor oil spill, benthic population studies in Buzzards Bay (Sanders, H.L. 1960, Sanders, H.L. *et.al.*, 1980, Tian, Y.Q., J.J. Wang, J. A. Duff, B.L. Howes and A. Evgenidou. 2009) and New Bedford (Howes, B.L. and C.T. Taylor, 1990), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H’) and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 4 mg L^{-1}, in open water estuarine environments. Massachusetts State Water Quality Classifications indicate that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1}. The tidally influenced waters of the Tisbury Great Pond system are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality. It is through the MEP and TMDL processes that management actions are developed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Tisbury Great Pond system (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from August through mid-September. The majority of the mooring data from the Tisbury Great Pond system was collected during the summer of 2005. Only one mooring had to be redeployed in the summer of 2007 (Tisbury Great Pond-West) which measured over the same temporal period as in 2005.

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

Dissolved oxygen and chlorophyll-*a* records were evaluated both for temporal trends and to determine the percent of the 41 to 48 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

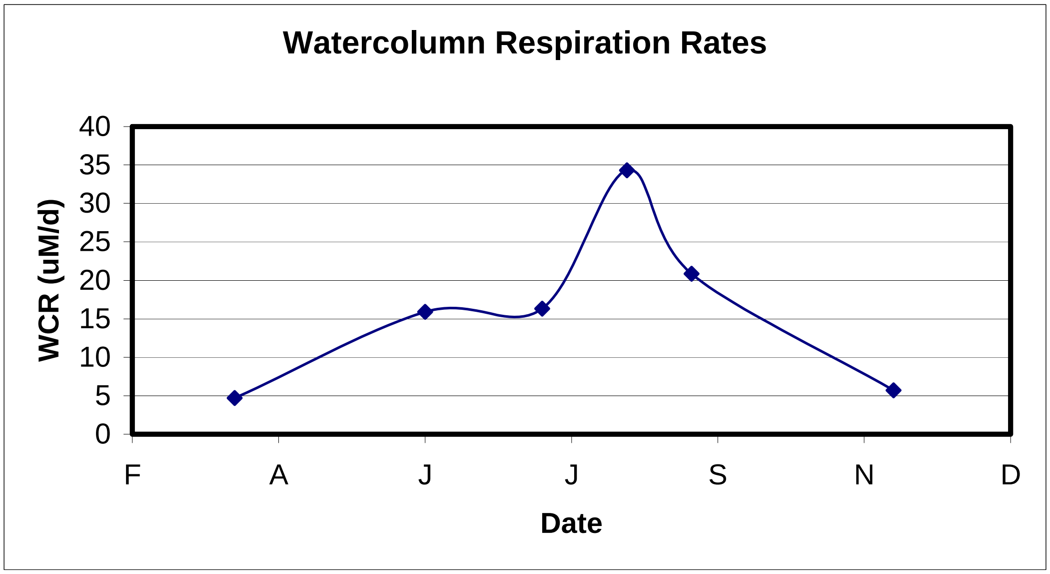

Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate moderately to highly nutrient enriched waters with higher nutrient related water quality in the main basin and Black Point Pond and greater levels of oxygen depletion and phytoplankton biomass in the Coves, such as Town Cove and Tiah Cove (Figures VII-3 through VII-14). It should be noted that the Water Quality Monitoring Program observed similar levels of chlorophyll and bottom water oxygen depletion in critical areas of the system, although did not always capture the minimum oxygen or maximum chlorophyll-*a* conditions at site. The oxygen data is consistent with a moderate to high level of organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-*a*. The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels are consistent with the nitrogen levels within the various basins (Section VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

The oxygen records show that the inner sub-embayments of Tisbury Great Pond, specifically Town Cove and Tiah Cove, which receive significant watershed nitrogen loads relative to their volumes and turnover rates, have the largest daily oxygen excursions, a nutrient related response. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The central region of Town Cove has clear evidence of oxygen levels above atmospheric equilibration providing additional documentation of potential impairment through nitrogen over-enrichment.

Figure VII-2. Aerial Photograph of the Tisbury Great Pond system in the Towns of Chilmark and West Tisbury showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2005 and 2007.

Measured dissolved oxygen depletion indicates that sub-basins to the Tisbury Great Pond Embayment System, such as the Town Cove and Tiah Cove, and to a lesser extent, the main lagoonal basin formed behind the barrier beach, show high to moderate levels of oxygen stress respectively, as does bottom water oxygen data from the monitoring program (1995-2010). The largest oxygen depletions and excursions were observed in Town Cove, which receives large quantities of groundwater and surface water transported nutrient load from the watershed. The observed spatial pattern indicated that the level of oxygen depletion (Table VII-1) and chlorophyll-*a* (Table VII-2) and total nitrogen levels increased with increasing distance from the tidal inlet, periodically created through the barrier beach. This temporary inlet opening serves to lower pond and associated groundwater levels, but also provides the most promising mechanism for restoration of pond habitats presently impaired due to nitrogen enrichment by exchanging nitrogen and organic matter enriched pond waters with high quality waters of the

Atlantic Ocean. The Water Quality Monitoring Program, while not yielding insight into the short-term temporal variation in oxygen and chlorophyll, does yield a good baseline for looking at the spatial distribution. The results support the mooring data, also indicating high to moderate levels of nitrogen enrichment depending on the location in the overall pond system and a moderate level of enrichment in the main basin of Tisbury Great Pond. Measured bottom water oxygen depletion followed this same pattern as did the gradient in chlorophyll.

The pattern of oxygen depletion, elevated chlorophyll-*a* and nitrogen levels are consistent with the present lack of eelgrass (Section VII.3) and quality of infaunal habitats (Section VII.4) throughout the Tisbury Great Pond Embayment System. These assessments indicate an estuarine system that is beyond its ability to assimilate nitrogen loads without impairment. The embayment specific results are as follows:

Tisbury Great Pond – Main Basin West (Figures VII-3 and VII-4):

The Tisbury Great Pond-West mooring was located within the main basin in the lower portion of the pond and off towards the southwestern side of the lower basin (Figure VII-2). Daily excursions (maximum to minimum) in oxygen levels at this location were slight, generally varying only 2 mg L^{-1}. Oxygen levels varied primarily with light (diurnal cycle) as the pond system was closed during the deployment period and therefore could not be affected by tidal exchange. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). In addition, maximum oxygen levels did not exceed air equilibration (% air saturation), which occurs when nitrogen enrichment has stimulated phytoplankton production and oxygen release. Both the absence of high oxygen levels (>10 mg L^{-1}) and the small daily excursion suggest that significant organic matter enriched conditions were not extant in this region of the basin during the measurement period.

Oxygen levels were generally above 6 mg L^{-1} (90% of record) and only infrequently declined to between 5 and 6 mg L^{-1} for 10% of the 42 day record (Figure VII-3). These values are comparable to the results from the long-term Water Quality Monitoring Program sampling at this location. Oxygen levels at this site in lower portion of Tisbury Great Pond were always >4 mg L^{-1}, the critical threshold for oxygen stress in an estuarine system (Table VII-1). The infrequent oxygen declines were consistent with the moderate to low levels of phytoplankton biomass as measured by chlorophyll-*a*. Chlorophyll-*a* averaged 11.0 ug L^{-1} over the record and only exceeded 15 ug L^{-1} 12% of the deployment period, rarely reaching 20 ug L^{-1}. The *chlorophyll-a* levels were elevated, but constant and did not indicate any pronounced bloom during the 42 day measurement period. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality in temperate embayments, a level approximately the same as the average chlorophyll-*a* observed in this part of the lower main basin by the mooring and a level slightly higher than what was obtained by the Water Quality Monitoring Program (9 ug L-1). These levels of chlorophyll-*a* are indicative of an open water basin with low to moderate nitrogen and organic matter enrichment (Table VII-2, Figure VII-4), which is resulting in only minor oxygen depletion.

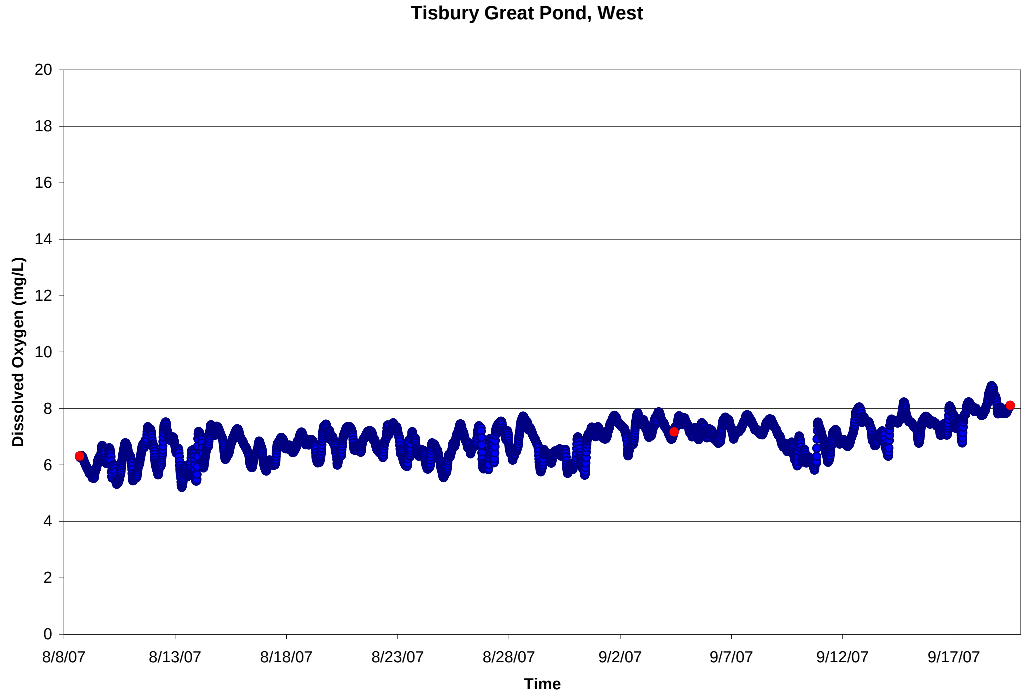

Figure VII-3. Bottom water record of dissolved oxygen at the Tisbury Great Pond-West station, Summer 2007 (location in Figure VII-2). Calibration samples represented by red dots.

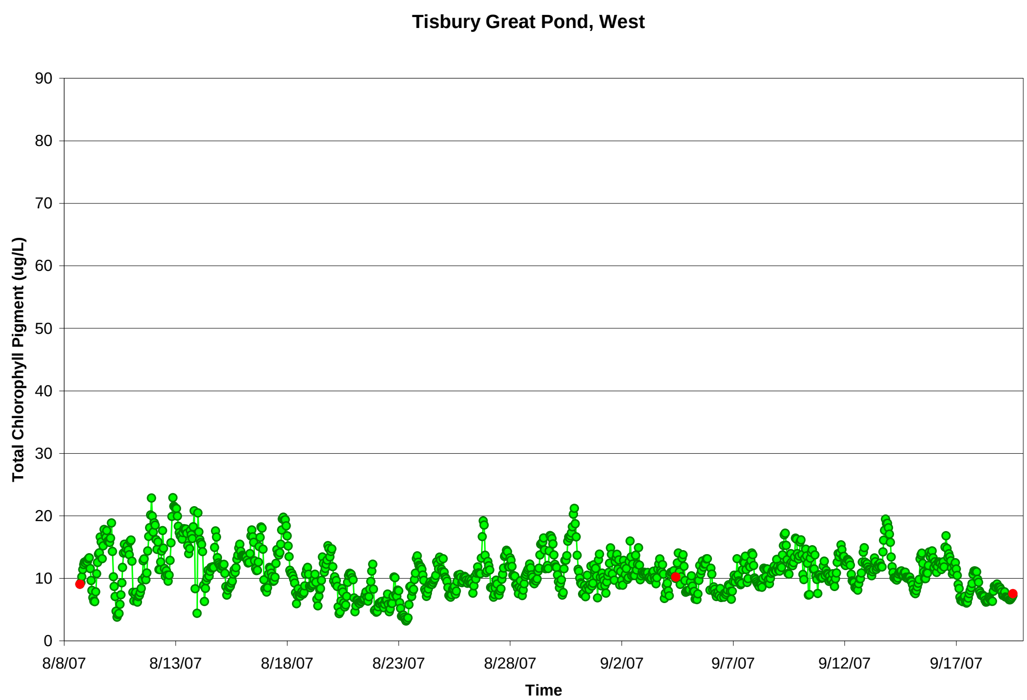

Figure VII-4. Bottom water record of Chlorophyll-*a* in the Tisbury Great Pond-West station, Summer 2007. Calibration samples represented as red dots.

Tisbury Great Pond- Main Basin Southeast (Figures VII-5 and VII-6):

The Tisbury Great Pond-Southeast mooring was located in the lower portion of the main basin along the southeastern shore just south of the mouth of Deep Bottom Cove (Figure VII-2). Oxygen varied primarily with light (diurnal cycle) as the pond system was closed during the deployment period and therefore could not be affected by the tide. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Daily excursions in oxygen levels at this location were 2-3 times larger than at the lower basin western mooring site, frequently changing 4 to 5 mg L^{-1} from day to night. However, maximum oxygen levels did not exceed air equilibration (% air saturation), which occurs at high levels of nitrogen enrichment sufficient to stimulate phytoplankton production (oxygen release). The absence of high oxygen levels (>10 mg L^{-1}), but large daily excursion are indicative of a system with moderate nitrogen and organic matter enrichment.

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 46% and 21% of the 48 day record respectively (Figure VII-5). Moreover, oxygen levels periodically dropped below 3 mg L^{-1}, below the oxygen stress threshold of 4 mg/L (Table VII-1). The frequent and significant oxygen declines were consistent with the elevated levels of phytoplankton biomass as measured by chlorophyll-*a*. Chlorophyll-*a* averaged 10.3 ug L^{-1} over the record, frequently exceeding 15 ug L^{-1} (15% of record) and showing periodic blooms to 30 ug L^{-1}. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality in temperate embayments. Both the extent of oxygen depletion and the levels of chlorophyll are indicative of a sub-basin with moderate nitrogen and organic matter enrichment (Table VII-2, Figure VII-6).

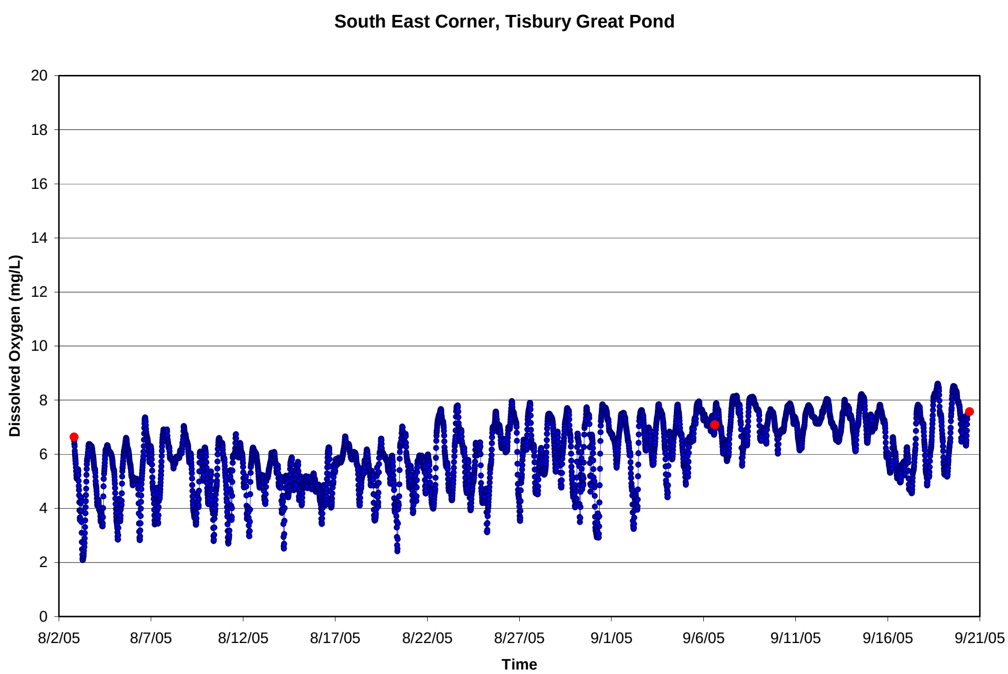

Figure VII-5. Bottom water record of dissolved oxygen recorded within the southeastern portion of the main basin of Tisbury Great Pond, summer 2005 (location in Figure VII-2). Calibration samples represented as red dots.

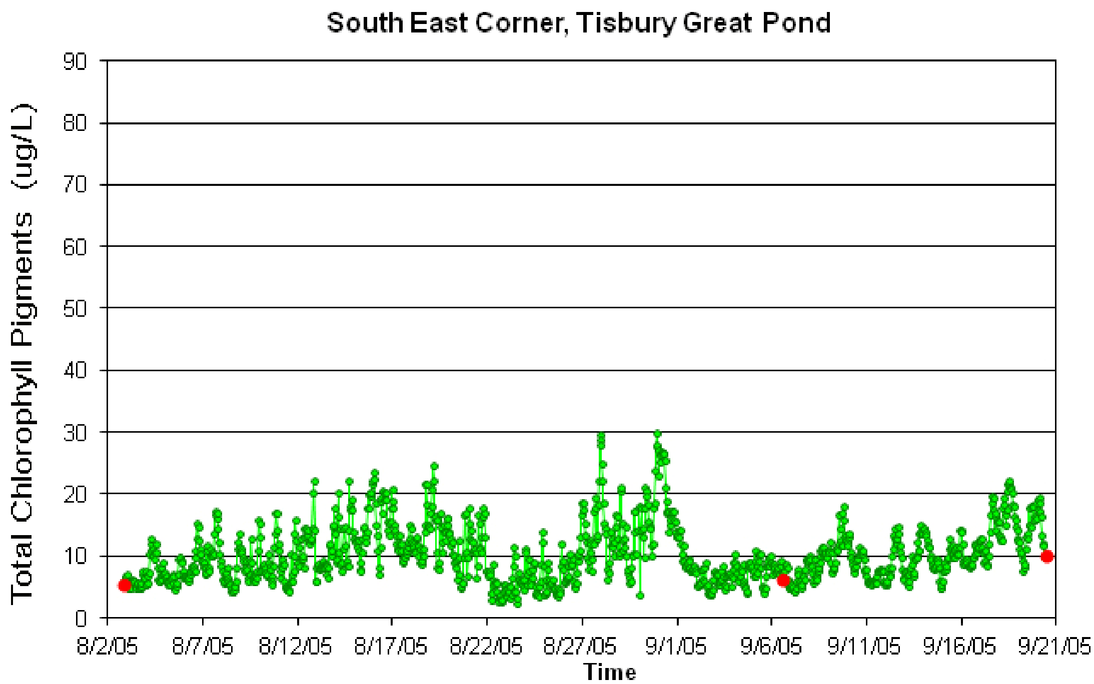

Figure VII-6. Bottom water record of Chlorophyll-*a* recorded within the southeastern portion of the main basin of Tisbury Great Pond, summer 2005 (location in Figure VII-2). Calibration samples represented as red dots.

Tisbury Great Pond-Town Cove Middle (Figures VII-7 and VII-8)

The Tisbury Great Pond-Town Cove Middle mooring site was located within the mid reach of Town Cove, upgradient of the confluence of Pear Tree Cove and Town Cove but down gradient of where the Tiasquam River discharges into Town Cove (Figure VII-2). Oxygen varied primarily with light (diurnal cycle) as the pond system was closed during the deployment period and therefore could not be affected by the tide. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Extreme daily excursions in oxygen levels were observed at this location, frequently changing as much as 12 mg L^{-1} with from day to night. Maximum oxygen levels exceeded air equilibration (% air saturation), frequently exceeding 10 mg L^{-1} and even 14 mg L^{-1}. These high levels occur at high levels of nitrogen enrichment sufficient to stimulate phytoplankton production (oxygen release). The very large daily excursions and very high maximum oxygen levels are indicative of a system with significant nitrogen and organic matter enrichment.

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 37% and 25% of the 48 day record respectively (Figure VII-7). Moreover, oxygen levels frequently declined below 4 mg L^{-1} and even 3 mg L^{-1}, 14% and 7 % of the deployment period, respectively, well below the oxygen stress threshold of 4 mg/L (Table VII-1). Equally important was the prolonged periods at hypoxic levels, <2 mg L^{-1}. The frequent and significant oxygen declines are indicative of high levels of organic matter enrichment consistent with the high levels of phytoplankton biomass as measured by chlorophyll-*a*. Chlorophyll-*a* averaged 15.2 ug L^{-1} over the 48 day record and was consistently >10 ug L^{-1}, 69% of time and showed blooms of >30 ug L^{-1}. Results from the Water Quality Monitoring Program within the mid reach of Town Cove also showed chlorophyll-*a* levels averaging >11-16 ug L^{-1} in the multi-year monitoring. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality, a level well below the average chlorophyll-*a* observed in this basin. Both the extent of oxygen depletion and the levels of chlorophyll are indicative of an estuarine reach with significant nitrogen and organic matter enrichment at levels associated with habitat impairment in many embayments (Table VII-2, Figure VII-8).

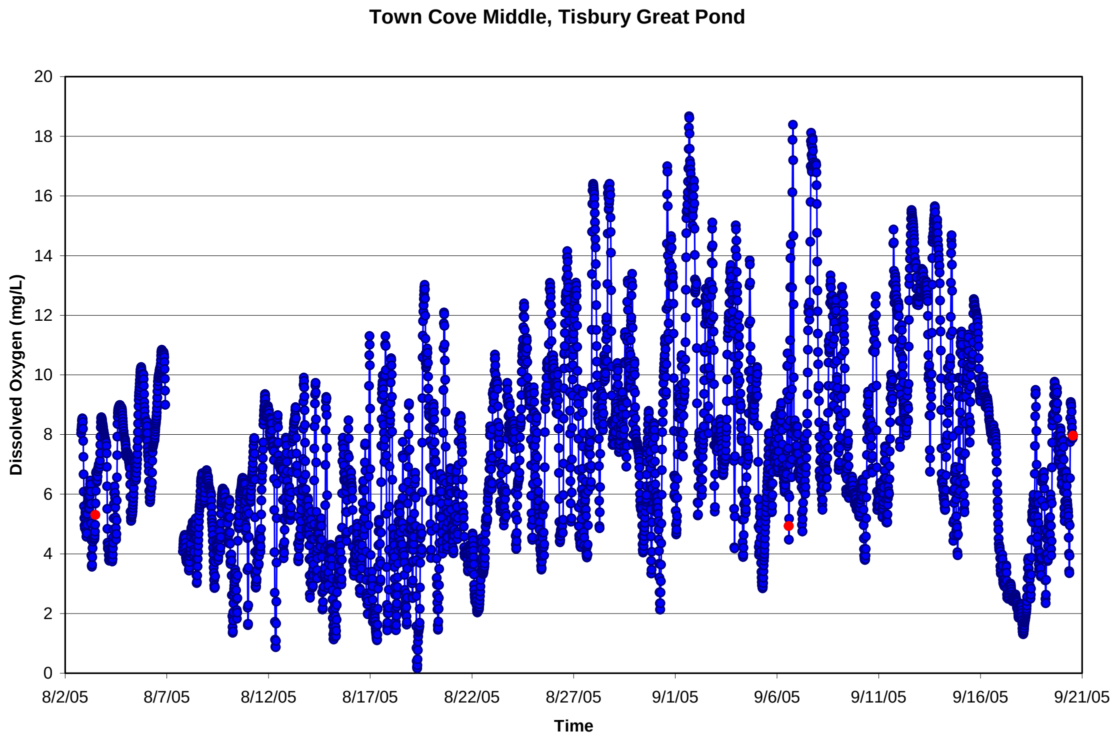

Figure VII-7. Bottom water record of dissolved oxygen within the mid reach of Town Cove, Tisbury Great Pond, summer 2005 (Figure VII-2). Calibration samples shown as red dots.

Tisbury Great Pond-Town Cove Lower (Figures VII-9 and VII-10)

The Tisbury Great Pond-Town Cove Lower mooring site was located within the lower reach of Town Cove, near the confluence with Short Cove at the entry to the lower main great pond basin (Figure VII-2). Oxygen varied primarily with light (diurnal cycle) as the pond system was closed during the deployment period and therefore could not be affected by the tide. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Although much smaller than the daily excursions in oxygen levels within the mid-reach of Town Cove, the lower reach still showed large daily oxygen excursions, frequently changing as much as 5 mg L^{-1} with from day to night. However, maximum oxygen levels did not exceed air equilibration (% air saturation), and only infrequently reached 10 mg L^{-1}. The large daily excursions is indicative of a system with nitrogen and organic matter enrichment.

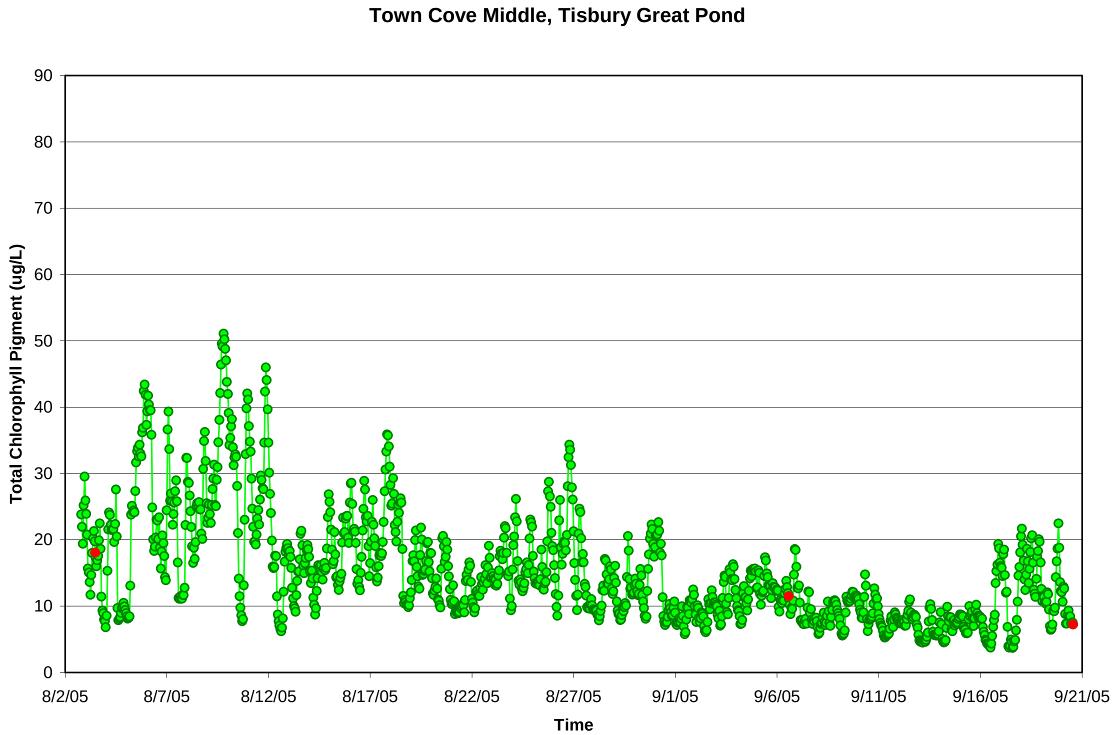

Figure VII-8. Bottom water record of Chlorophyll-*a* within the mid reach of Town Cove, Tisbury Great Pond, summer 2005 (location in Figure VII-2). Calibration samples shown as red dots.

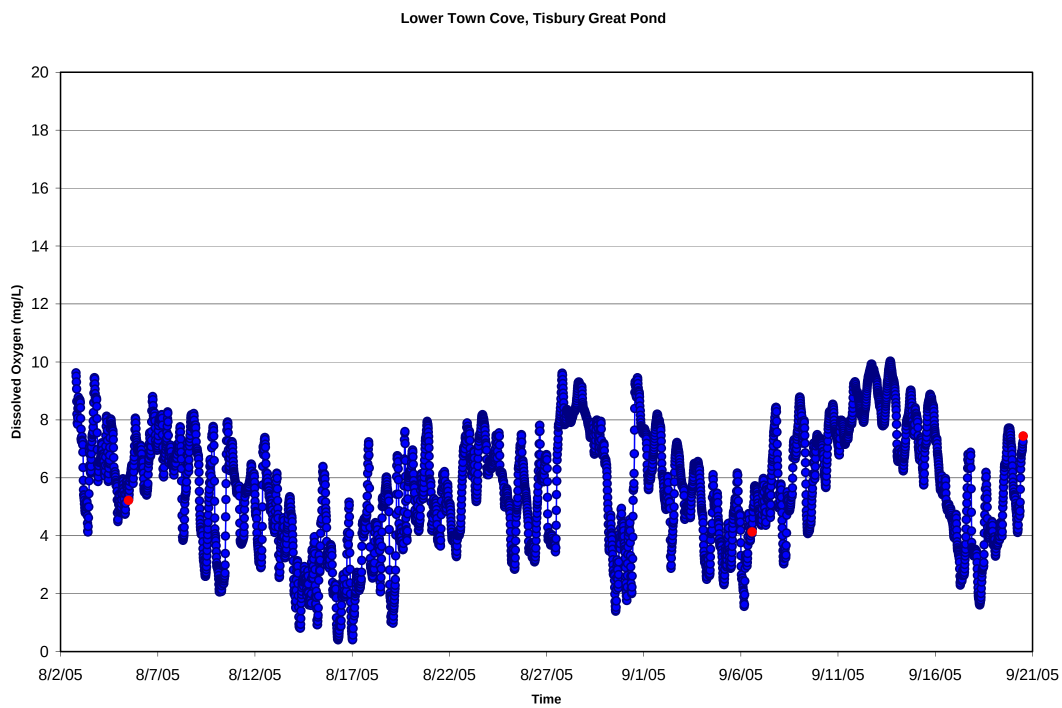

Figure VII-9. Bottom water record of dissolved oxygen within the lower reach of Town Cove, Tisbury Great Pond, summer 2005 (Figure VII-2). Calibration samples shown as red dots.

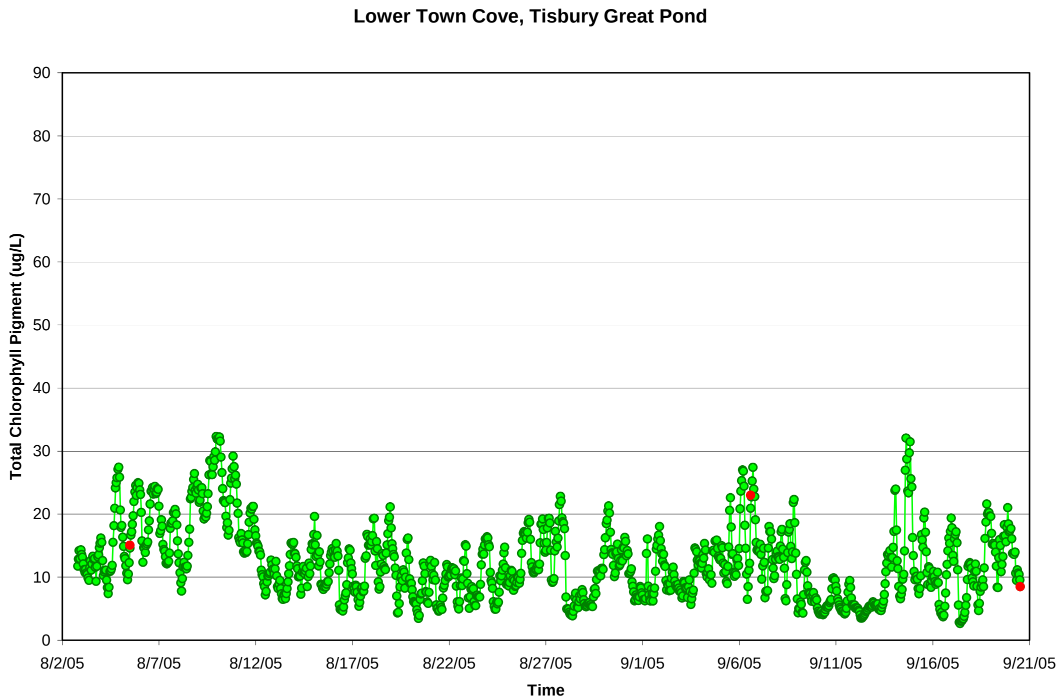

Figure VII-10. Bottom water record of Chlorophyll-*a* within the lower reach of Town Cove, Tisbury Great Pond, summer 2005 (location in Figure VII-2). Calibration samples shown as red dots.

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 54% and 38% of the 48 day record respectively (Figure VII-9). Moreover, oxygen levels were frequently <4 mg L-1, periodically declining below 3 mg L^{-1} for 11 % of the deployment period, well below the oxygen stress threshold of 4 mg/L (Table VII-1). Equally important was the prolonged periods at hypoxic levels, <2 mg L^{-1}. The frequent and significant oxygen declines are indicative of high levels of organic matter enrichment consistent with the high levels of phytoplankton biomass as measured by chlorophyll-*a*. Chlorophyll-*a* averaged 12.3 ug L^{-1} over the 48 day record, was consistently >10 ug L^{-1} and >15 ug L^{-1}, 62% and 27% of time and showed periodic blooms of >25 ug L^{-1}. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality, a level well below the average chlorophyll-*a* observed in this basin. Both the extent of oxygen depletion and the levels of chlorophyll are indicative of an estuarine reach with significant nitrogen and organic matter enrichment at levels associated with habitat impairment in many embayments (Table VII-2, Figure VII-10).

Tisbury Great Pond-Tiah Cove (Figures VII-11 and VII-12):

The Tisbury Great Pond-Tiah Cove mooring site was centrally located within the lower reach of this tributary sub-basin to the main basin of the great pond, just down-gradient of the constriction dividing the upper and lower basins of Tiah Cove (Figure VII-2). Oxygen varied primarily with light (diurnal cycle) as the pond system was closed during the deployment period and therefore could not be affected by the tide. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). The lower reach of Tiah Cove showed moderate daily oxygen excursions, generally ~4 mg L^{-1} from day to night. Maximum daily oxygen levels generally were near air equilibration

(% air saturation), and rarely exceeded 8 mg L^{-1}. The moderate daily excursions is indicative of a system with moderate levels of nitrogen and organic matter enrichment.

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 51% and 26% of the 48 day record respectively (Figure VII-11). Moreover, oxygen levels periodically declined to less than 4 mg L^{-1} (11 % of the deployment period), and periodically declined to ~2 mg L^{-1}, well below the oxygen stress threshold of 4 mg/L (Table VII-1). The frequent and significant oxygen declines are indicative of high levels of organic matter enrichment consistent with the high levels of phytoplankton biomass as measured by chlorophyll-*a*. Chlorophyll-*a* was very high within Tiah Cove, averaging 27.4 ug L^{-1} over the 48 day record, with frequent blooms of >40 ug L^{-1}. Results from the Water Quality Monitoring Program, which in recent years (2009-2011) began sampling the lower basin of Tiah Cove, captured more modest chlorophyll-*a* levels averaging ~10 ug L^{-1} with blooms to ~20 ug L^{-1}, consistent with nitrogen enriched conditions. The lower levels captured by the traditional monitoring program was likely related to the relatively short record of monitoring of this station. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality, a level well below the average chlorophyll-*a* observed in this basin. Both the extent of oxygen depletion and the levels of chlorophyll are indicative of an estuarine reach with significant nitrogen and organic matter enrichment at levels associated with habitat impairment in many embayments (Table VII-2, Figure VII-12).

Tisbury Great Pond-Deep Bottom Cove (Figures VII-13 and VII-14)

The Tisbury Great Pond-Deep Bottom Cove mooring site was located within the middle reach of Deep Bottom Cove (Figure VII-2). Oxygen varied primarily with light (diurnal cycle) as the pond system was closed during the deployment period and therefore could not be affected by the tide. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). Daily excursions in oxygen levels were modest, generally ~2 mg L^{-1} from day to night. In addition, maximum oxygen levels did not exceed air equilibration (% air saturation), and only infrequently exceeded 8 mg L^{-1}. The modest daily excursions and lack of oxygen levels over air equilibration is indicative of a system with moderate nitrogen and organic matter enrichment.

Oxygen levels frequently declined below 6 mg L^{-1} and 5 mg L^{-1}, for 33% and 12% of the 48 day record respectively (Figure VII-13). However, large depletions of oxygen were not observed, and oxygen levels rarely declined to <4 mg L^{-1}, the oxygen stress threshold of 4 mg L^{-1} (Table VII-1). The moderate levels of oxygen depletion are indicative of a moderate level of organic matter enrichment, slightly less than might be expected from the parallel measures of phytoplankton biomass as measured by chlorophyll-*a*. Chlorophyll-*a* averaged 18.6 ug L^{-1} over the 48 day record, was consistently >15 ug L^{-1} and frequently >25 ug L^{-1}, 61% and 23% of time and showed periodic blooms of >30 ug L^{-1}. Average summer chlorophyll levels over 10 ug L^{-1} have been used to indicate impaired nitrogen related water quality, a level well below the average chlorophyll-*a* observed in this basin. Both the extent of oxygen depletion and the levels of chlorophyll are indicative of an estuarine reach with significant nitrogen and organic matter enrichment at levels associated with habitat impairment in many embayments (Table VII-2, Figure VII-14).

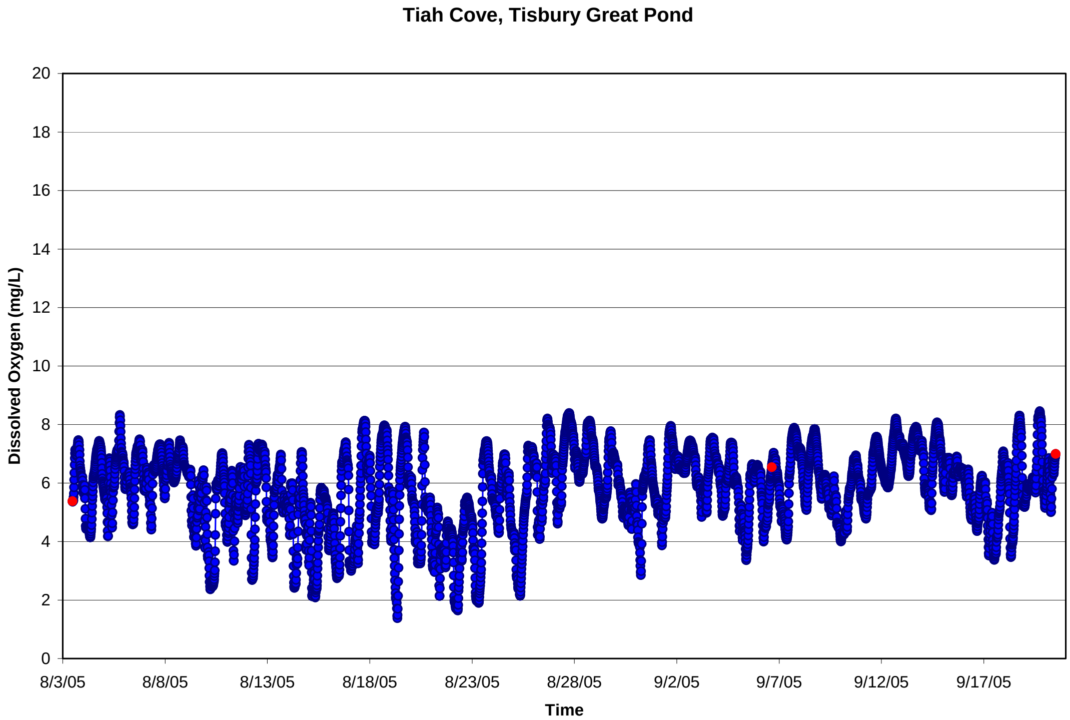

Figure VII-11. Bottom water record of dissolved oxygen within the lower reach of Tiah Cove, Tisbury Great Pond, summer 2005 (Figure VII-2). Calibration samples shown as red dots.

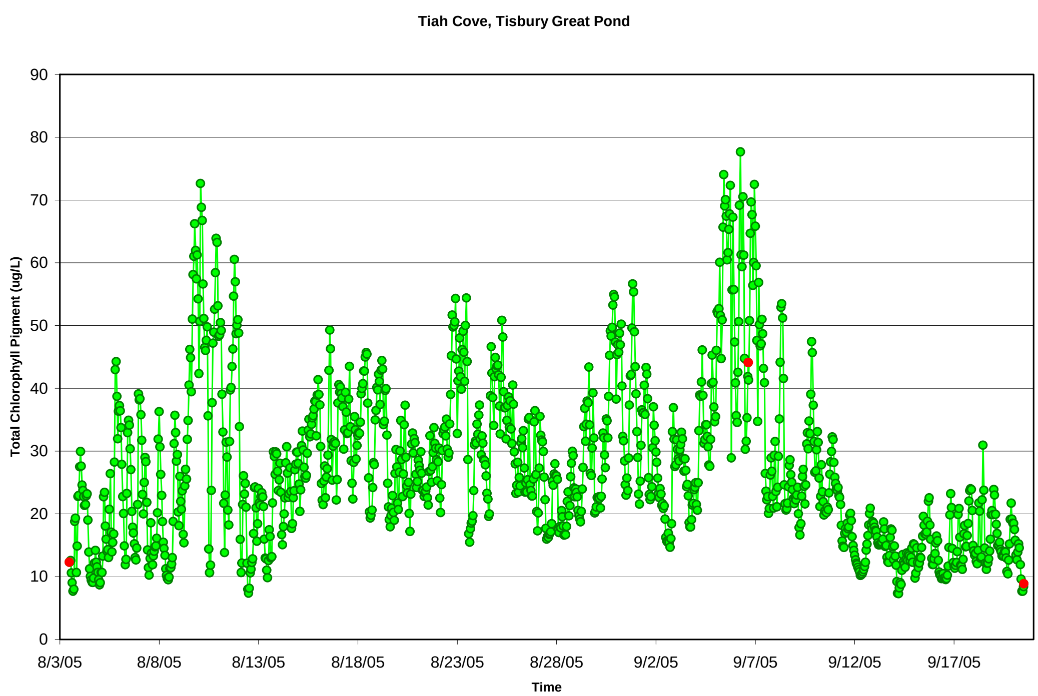

Figure VII-12. Bottom water record of Chlorophyll-*a* within the lower reach of Tiah Cove, Tisbury Great Pond, summer 2005 (location in Figure VII-2). Calibration samples shown as red dots.

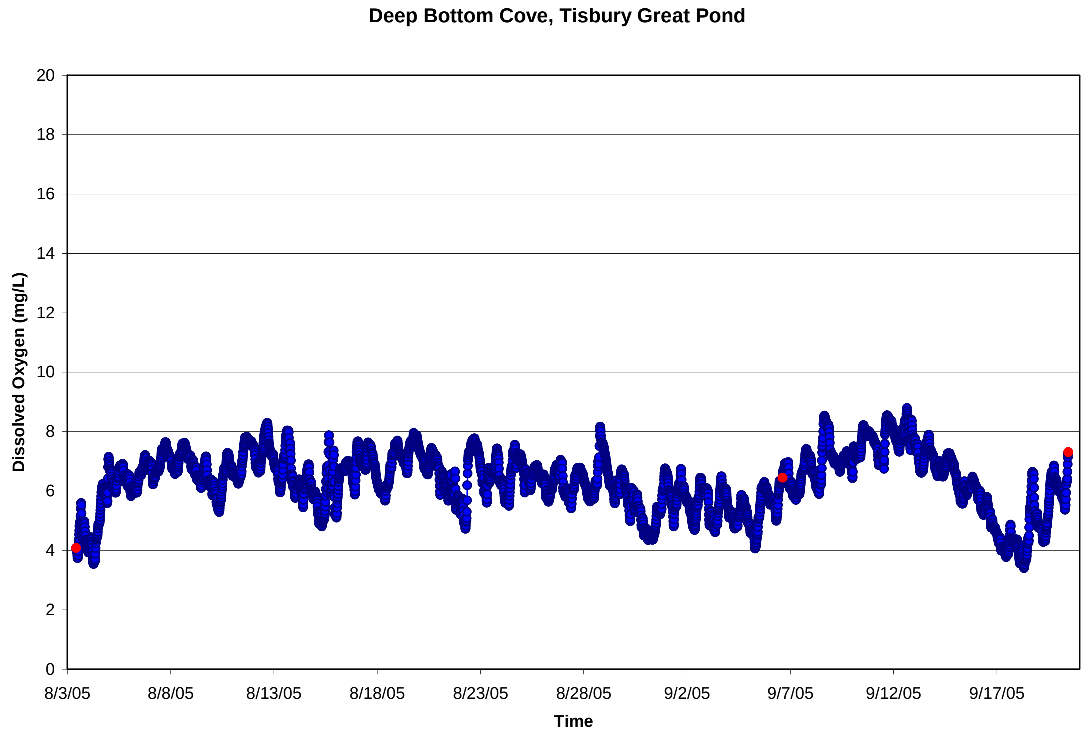

Figure VII-13. Bottom water record of dissolved oxygen within the mid reach of Deep Bottom Cove, Tisbury Great Pond, summer 2005 (Figure VII-2). Calibration samples shown as red dots.

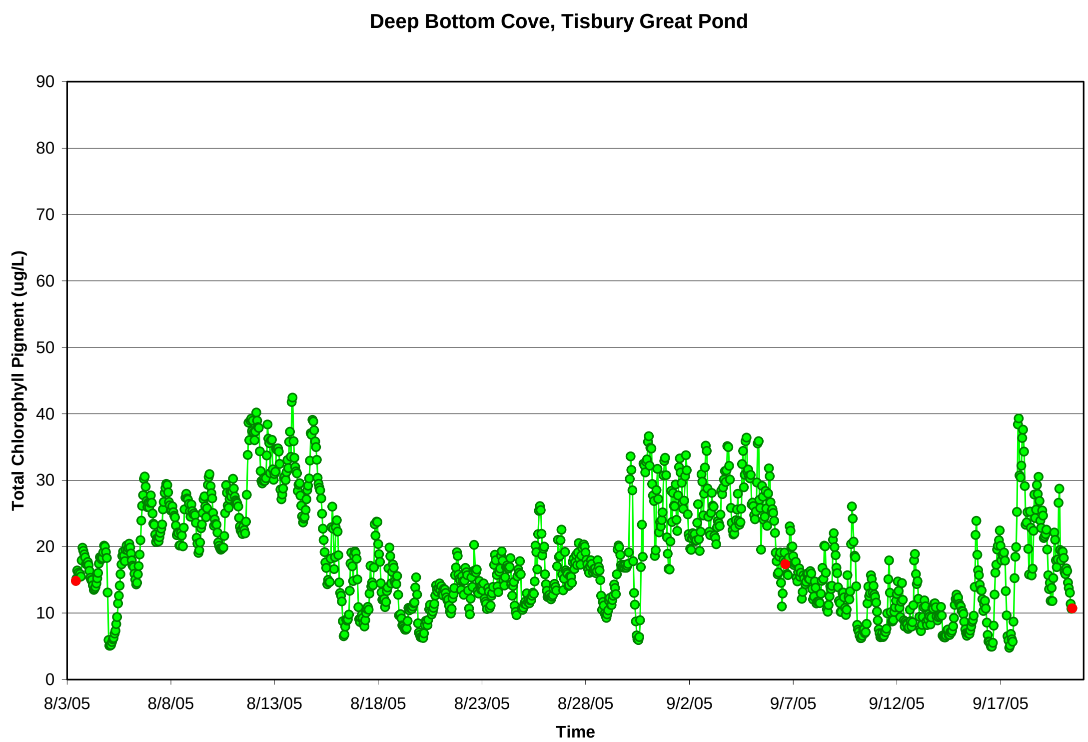

Figure VII-14. Bottom water record of Chlorophyll-*a* within the mid reach of Deep Bottom Cove, Tisbury Great Pond, summer 2005 (Figure VII-2). Calibration samples shown as red dots.

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.

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Town Cove Lower	**8/2/2005**	**9/20/2005**	**48.7**	**54%**	**38%**	**23%**	**11%**
			Mean	0.51	0.33	0.23	0.17
			Min	0.02	0.01	0.01	0.01
			Max	2.34	1.61	1.44	0.75
			S.D.	0.54	0.36	0.27	0.20
Town Cove Mid	**8/2/2005**	**9/20/2005**	**48.76**	**37%**	**25%**	**14%**	**7%**
			Mean	0.20	0.16	0.11	0.11
			Min	0.01	0.01	0.01	0.01
			Max	1.83	1.65	1.54	0.84
			S.D.	0.27	0.24	0.21	0.16
Tisbury Great Pond East	**8/2/2005**	**9/20/2005**	**48.63**	**46%**	**21%**	**6%**	**1%**
			Mean	0.42	0.17	0.10	0.05
			Min	0.02	0.01	0.02	0.02
			Max	2.89	0.64	0.24	0.16
			S.D.	0.46	0.14	0.06	0.04
Tisbury Great Pond West	**8/8/2007**	**9/19/2007**	**41.8**	**10%**	**0%**	**0%**	**0%**
			Mean	0.17	N/A	N/A	N/A
			Min	0.01	0.00	0.00	0.00
			Max	0.51	0.00	0.00	0.00
			S.D.	0.15	N/A	N/A	N/A
Tiah Cove	**8/3/2005**	**9/20/2005**	**48.03**	**51%**	**26%**	**11%**	**4%**
			Mean	0.39	0.20	0.16	0.14
			Min	0.01	0.01	0.01	0.01
			Max	2.82	1.30	0.42	0.28
			S.D.	0.45	0.22	0.13	0.10
Deep Bottom Cove	**8/3/2005**	**9/20/2005**	**48.03**	**33%**	**12%**	**2%**	**0%**
			Mean	0.26	0.24	0.09	N/A
			Min	0.01	0.01	0.02	0.00
			Max	2.50	1.78	0.23	0.00
			S.D.	0.45	0.41	0.07	N/A

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

Mooring Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Town Cove Lower	**8/2/2005**	**9/20/2005**	**48.8**	**93%**	**62%**	**27%**	**11%**	**3%**
Mean Chl Value = 12.3 ug/L			**Mean**	2.28	0.55	0.29	0.27	0.21
			Min	0.04	0.04	0.04	0.04	0.08
			Max	13.58	4.17	2.83	1.00	0.71
			S.D.	3.68	0.69	0.43	0.25	0.21
Town Cove Mid	**8/2/2005**	**9/20/2005**	**48.96**	**97%**	**69%**	**40%**	**22%**	**12%**
Mean Chl Value = 15.2 ug/L			**Mean**	9.53	0.71	0.37	0.27	0.23
			Min	0.79	0.04	0.04	0.04	0.04
			Max	41.29	5.42	2.63	2.08	1.29
			S.D.	17.77	1.06	0.47	0.37	0.29
Tisbury Great Pond East	**8/2/2005**	**9/20/2005**	**48.70**	**92%**	**44%**	**15%**	**4%**	**1%**
Mean Chl Value = 10.3 ug/L			**Mean**	1.45	0.34	0.19	0.14	0.19
			Min	0.04	0.04	0.04	0.04	0.13
			Max	9.00	1.96	0.83	0.58	0.29
			S.D.	2.23	0.40	0.18	0.15	0.09
Tisbury Great Pond West	**8/8/2007**	**9/19/2007**	**41.7**	**98%**	**59%**	**12%**	**1%**	**0%**
Mean Chl Value = 11.0 ug/L			**Mean**	4.54	0.39	0.17	0.09	N/A
			Min	0.04	0.04	0.04	0.04	0.00
			Max	26.96	1.54	0.79	0.21	0.00
			S.D.	8.64	0.38	0.17	0.07	N/A
Tiah Cove	**8/3/2005**	**9/20/2005**	**48.20**	**99.9%**	**97%**	**82%**	**68%**	**49%**
Mean Chl Value = 27.4 ug/L			**Mean**	48.17	4.25	1.20	0.70	0.39
			Min	48.17	0.04	0.04	0.04	0.04
			Max	48.17	31.67	20.00	5.42	3.42
			S.D.	N/A	9.21	3.69	1.16	0.52
Deep Bottom Cove	**8/3/2005**	**9/20/2005**	**48.10**	**99.7%**	**85%**	**61%**	**38%**	**23%**
Mean Chl Value = 18.6 ug/L			**Mean**	15.99	1.58	0.67	0.49	0.30
			Min	0.79	0.04	0.04	0.04	0.04
			Max	44.13	10.83	9.13	4.83	2.67
			S.D.	24.39	2.76	1.66	0.98	0.45

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass analysis of historical data was conducted for the Tisbury Great Pond Embayment System by the MassDEP Eelgrass Mapping Program as part of the MEP. Analysis of available aerial photos from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. The 1951 data were only anecdotally validated. In addition, qualitative field observations of eelgrass have been made by a variety of scientists ranging from MEP Technical Team in 2005 and 2007 and MVC staff (W. Wilcox) as well as the Town of Chilmark Shellfish Propagation Agent (I. Scheffer), a Town of Chilmark citizen (K. Healy) and Mr. Mal Jones, resident of West Tisbury and long term Tisbury Great Pond Steward. While these latter observations do not lend themselves to mapping of eelgrass coverage, they provide critical information on the absence/presence of eelgrass within this great salt pond and its general locations, depths and density, where present. These data form the basis of the MEP eelgrass assessment for this estuary.

The primary use of the MEP eelgrass assessment for an estuary is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 2011 (Figure VII-15); 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 and the potential recoverable acreages should it be determined that habitat loss has occurred.

Over the past several decades, eelgrass has generally not existed within the Tisbury Great Pond Embayment System. At present, given moderate levels of watershed nitrogen loading and limited tidal exchange only periodically occurring during managed breaches of the barrier beach, the nitrogen, chlorophyll and oxygen levels within the pond basins are not supportive of eelgrass. In addition, much of the system has structural impediments to supporting eelgrass even at moderate levels of nitrogen enrichment. The central region of the main basin and much of Deep Bottom and Town Coves are relatively deep requiring clearer waters (light penetration) than many shallow tidal estuaries within the region. The lack of strong gradients in water quality have been documented from the long-term water quality monitoring data, although a gradient does exist with higher levels of nutrients, organic matter and chlorophyll-*a* found in the Coves and lower levels within the main great pond basin. In addition, stronger periodic short-term gradients in chlorophyll and other parameters do occur during and shortly following a pond opening (see Section VI and Section VII.2).

All recent observations indicate an absence of eelgrass beds within the Tisbury Great Pond Embayment System. MEP technical staff did not find any evidence of eelgrass within the main basin or within the major tributary coves while conducting MEP related data collection (infaunal sampling and sediment core collection by diver for sediment nutrient flux determination). The MEP observations are consistent with the lack of eelgrass as confirmed by the Town of Chilmark Shellfish Propagation Agent (personal communication with I. Scheffer, 06/2012). Mr. Scheffer did indicate that in the seven (7) years he has been working on the pond, he has not observed eelgrass with the exception of one event approximately 3 years ago (2009) where following several openings of the pond that were several months in duration, a very small (~ 1 m^2) and thin patch of eelgrass was observed at the southern end of the pond close to the location where the barrier beach had been breached. This small patch of eelgrass did not persist and was only present for a short period of time. While this is anecdotal and qualitative information, it does indicate that under improved flushing and water quality

Figure VII-15. Historical Eelgrass bed distribution within the Tisbury Great Pond System. The 1951 baseline coverage is outlined in green and was developed by the MassDEP Eelgrass Mapping Program using aerial photography and photo interpretation techniques. As the pond is closed most of the time, subsequent surveys by the MassDEP in 1995, 2001 and 2006 did not include the waters of Tisbury Great Pond. Coves and Black Point Pond contained no discernible eelgrass coverage in 1951.

conditions, it may be possible for eelgrass to re-establish itself in some areas of Tisbury Great Pond. It is also critical to note that based on recently obtained (March 28, 2013) information about historical eelgrass in Tisbury Great Pond dating back to the 1950's, it is not unrealistic for eelgrass to re-establish itself in appropriate areas where eelgrass has existed in the past assuming water quality is restored to conditions supportive of such a habitat. According to Mr. Mal Jones (resident of West Tisbury and long-time Tisbury Great Pond Steward), eelgrass was historically present in Tisbury Great Pond in shallower waters of the main lower basin. Mr. Jones grew up in West Tisbury, worked on Tisbury Great Pond and started as a pond steward back when openings through the barrier beach were cut by hand. Mr. Jones indicated (B. Howes personal communication) that he was personally associated with Tisbury Great Pond from the 1940's to date. In the 1950's Mr. Jones was working for an oyster company within Tisbury Great Pond and was clear that while he did not know the full distribution of eelgrass in the 1950's, through his regular working on the pond he was definite that there were dense eelgrass beds within the footprint indicated by the MassDEP Mapping Program in the shallow area along the eastern shore of the main basin. He indicated that region to be south of the mouth of Deep Bottom Cove to the barrier beach. The MEP bathymetry indicates that this area has the greatest potential to support eelgrass. Mr. Jones was clear that the eelgrass was dense and that the water was clear and that the bottom of the pond could easily be seen from a boat. He also indicated that eelgrass from the pond would wash up in dense windrows along the shore, much like along Vineyard Sound today. He went further to indicate how the local folks would collect the dead eelgrass and use it.

The overall results indicate that eelgrass habitat within Tisbury Great Pond is impaired. While the coverage identified by the MassDEP Eelgrass Mapping Program (C. Costello) could not be quantified as to density or presence/absence of epiphytes, the southeastern side of the main basin between Tississa Pond and the barrier beach in waters generally 0.5 - 1.5 meters was determined to support eelgrass in 1951 based on the MassDEP Eelgrass Mapping program and consistent with anecdotal evidence. This bed is estimated to have had a maximum extent of up to 50 acres. The region of the 1951 eelgrass bed presently contains the most consolidated sand containing sediments with this great pond, consistent with an area that had supported eelgrass. The presence of eelgrass in this region is consistent with a low to moderately nitrogen enriched embayment system, most likely due to the lack of tidal flushing. The absence of eelgrass in 1951 within the coves and Black Point Pond is consistent with the structure of these basins. The Tisbury Great Pond eelgrass coverage is similar to that in Edgartown Great Pond using the MassDEP 1951 analysis. In Edgartown Great Pond 1951 coverage was also limited to the lower main basin and no habitat was identified within the numerous coves and upper main basin. However, some eelgrass has persisted and been observed in recent decades and in the MEP surveys of that system, adding support for the 1951 Edgartown Great Pond eelgrass coverage. The continuing presence of eelgrass in Edgartown versus Tisbury Great Pond is consistent with the lower chlorophyll-*a* and higher oxygen levels generally within Edgartown Great Pond. While it is not possible to determine the exact distribution and density of eelgrass in 1951, it does appear that there was historical dense eelgrass beds that has declined to zero based on more recent field observations.

The loss of eelgrass beds within the Tisbury Great Pond Embayment System relative to historical distribution (1951 photo interpretation and anecdotal historical account) is expected given the measured levels of nitrogen enrichment and resulting chlorophyll-*a* and dissolved oxygen. Total nitrogen levels (TN) within the lower basin have mean summer time levels of 0.51 - 0.53 mg N L^{-1} compared to the levels in other similarly configured southeastern Massachusetts estuarine basins currently supporting eelgrass, 0.35-0.45 mg N L^{-1} (range of Cape Cod systems). Other key water quality indicators, dissolved oxygen and chlorophyll-*a*, show similar levels of moderate enrichment with periodic oxygen depletions below 5 mg/L and chlorophyll levels in blooms reaching 10-20 ug/l. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, loss of eelgrass habitat within Tisbury Great Pond is consistent with areas of loss in numerous other estuaries throughout the region.

Other factors which influence eelgrass bed loss in embayments can also be at play in estuaries like the Tisbury Great Pond Embayment System, though the loss over the past 5 decades 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 there are virtually no mooring fields and no marinas within this "closed" system. Similarly, pier construction and boating pressure may be adding additional stress in nutrient enriched areas, but Tisbury Great Pond, again, has a very low intensity of these activities. It is not possible at this time to determine the potential effect of shellfishing on eelgrass loss in this system. At present there is no evidence that shellfishing pressure is sufficiently high as to be controlling eelgrass colonization in this estuary, and the oyster culture activities are focused on other areas within this embayment system.

Integrating all of the available eelgrass data, it appears that there has been significant loss of eelgrass coverage within Tisbury Great Pond, namely along the southeastern margin of the lower main basin. The loss has a potential extent of up to 50 acres, but the density cannot be fully quantified. This eelgrass loss indicates that this basin is presently supporting impaired eelgrass habitat and that restoration of this habitat should necessarily be part of nitrogen related restoration of the Tisbury Great Pond System. Based on modeling conducted as part of this effort, achieving a nitrogen threshold specific to the tributary coves will drive restoration of infaunal benthic habitat throughout the Tisbury Great Pond system and attaining a slightly lower threshold specific to the main basin will result in the restoration of eelgrass habitat in those areas suggested by historical evidence. Also, nitrogen management for eelgrass restoration will protect Black Point Pond from nitrogen over-enrichment, either directly through management of nitrogen sources within the Black Point Pond watershed or through lower nitrogen concentrations in the adjacent main basin waters. One clear management alternative for restoring any low to moderate impairment of Black Point Pond habitat, that needs to be evaluated, is to reduce the restriction of flow between Black Point Pond and Tisbury Great Pond currently caused by the occluded narrow channel connecting the two systems. Reducing the restriction will increase tidal exchange when Tisbury Great Pond is open to the low nitrogen Atlantic Ocean flood waters. While it appears that eelgrass habitat impairment is primarily within the lower main basin of the Tisbury Great Pond Embayment System, benthic animal habitat is also a critical estuarine resource which generally has a higher tolerance for nitrogen enrichment than eelgrass. Infauna habitat quality is the primary indicator of the health of embayment basins that naturally do not support eelgrass and therefore in important in the management of the tributary basins to the main basin of Tisbury Great Pond. Benthic animal habitat is evaluated in the section below.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling for benthic community characterization was conducted at 19 locations throughout the Tisbury Great Pond Embayment System (Figure VII-16). Sampling sites were located in Deep Bottom/Thumb Cove (4), Tiah Cove (3), Pear Tree Cove (1), Black Point Pond (3) and the lower main basin (7). At each site multiple assays were conducted. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high

D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the complete loss of eelgrass beds, the Tisbury Great Pond Embayment System is clearly impaired by nitrogen enrichment. However, much of this system, specifically all of its tributary sub-basins, have not historically supported eelgrass, so their present infaunal communities provide for a direct assessment of their nutrient related habitat quality. The benthic infauna analysis is important for determining the level of impairment (healthy→moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Section VIII).

Overall, the infauna survey indicated that most sub-basins comprising the Tisbury Great Pond Embayment System are presently near or beyond their ability to tolerate additional nitrogen inputs without impairment. The exception is Black Point Pond which is functionally a wetland basin (e.g. a pond surrounded by significant wetland area). There was a clear spatial pattern in habitat quality, with moderately to significantly impaired benthic animal habitat found in the upper tributary coves and the healthy to moderately impaired areas within the large main basin (and as noted, Black Point Pond). The Benthic Survey did not reveal any areas of severe degradation, as indicated by low numbers of individuals and species or dominance by opportunistic stress indicator species such as Capitellids and Tubificids. In fact, at all locations throughout the sub-basins of this embayment system, there were high numbers of individual (>600 per grab sample), moderate to high numbers of species (14 to 20 per sample) and low numbers of Capitellids and Tubificids (generally <10% of community), see Table VII-3. Species numbers of 20-25 generally indicate high quality benthic habitats. While there is little evidence of high levels of nitrogen related impairment of benthic animal communities, most areas did show clear evidence of low to moderate impairment associated with nitrogen and organic matter enrichment.

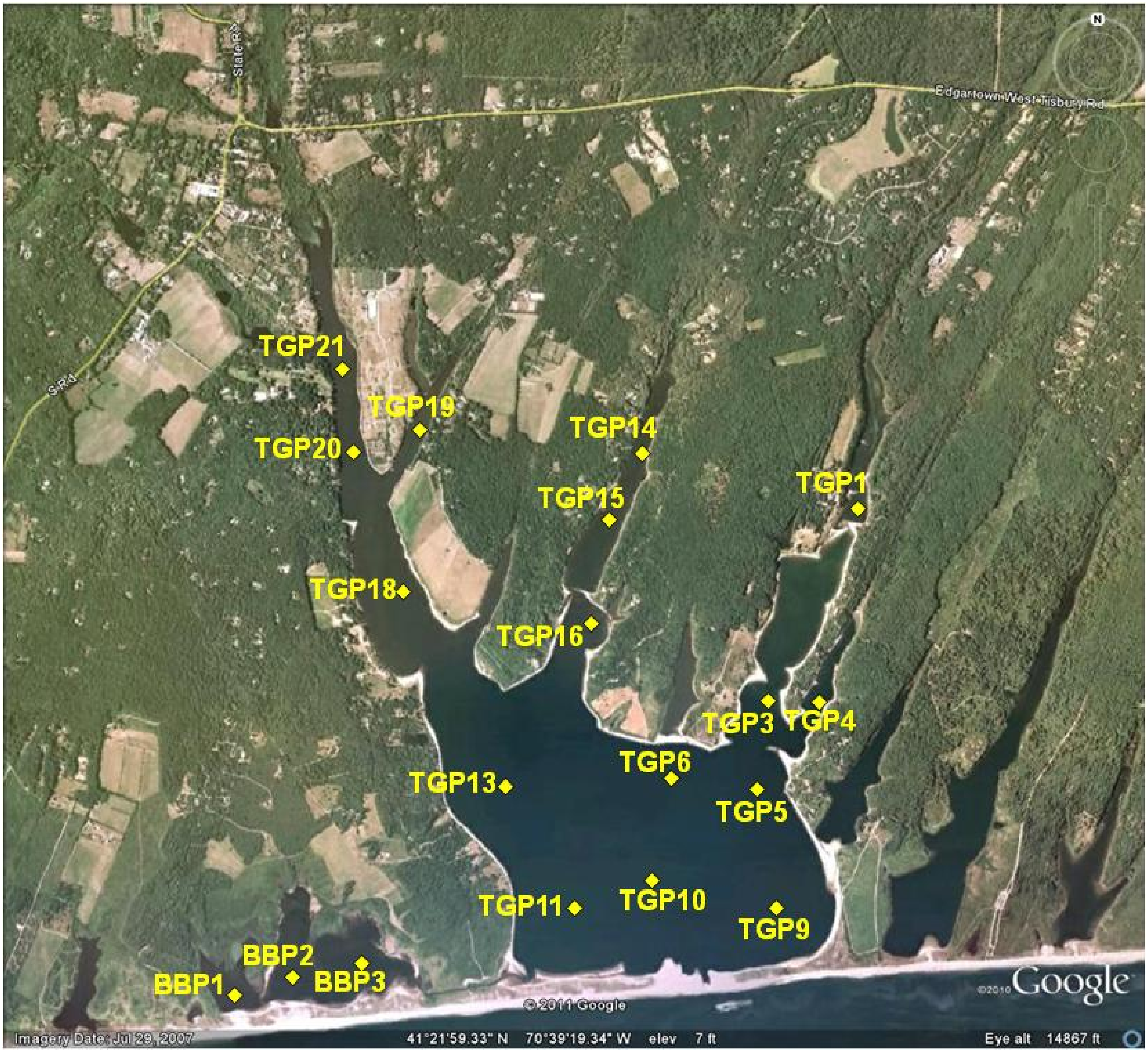

Figure VII-16. Aerial photograph of the Tisbury Great Pond Embayment System showing location of benthic infaunal sampling stations (yellow symbol). BBP indicates stations within Black Point Pond.

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.

Table VII-3. Benthic infaunal community data for the Tisbury Great 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 m^2. Stations refer to map in figure VII-16, replicate samples were collected at each location. S.E. is the standard error of the mean; N is the number of samples.

Basins	Station [1]	Actual Total Species	Actual Total Individuals	#Species Calc @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Tributary Basins	**TGP-**					
Pear Tree Cove	**19**	**14**	**1027**	**7**	**1.82**	**0.49**
Tiah Cove	**14,15,16**	**16**	**682**	**8**	**1.79**	**0.46**
Deep Bottom Cove [2]	**1,3,4**	**18**	**543**	**9**	**2.02**	**0.49**
Central Basin	**TGP-**					
Town Cove	**20,21**	**18**	**926**	**8**	**1.44**	**0.35**
Upper Basin	**13,18**	**15**	**2061**	**8**	**1.92**	**0.52**
Lower Basin	**5,6,9,10,12**	**20**	**1386**	**10**	**2.33**	**0.54**
Black Point Pond	**BPP-**					
Main Basin	**1,2,3**	**15**	**638**	**12**	**2.78**	**0.72**

1 - Station numbers refer to ID's on maps presented above.
2 - Deep Bottom Cove and Thumb Cove Combined.

The upper tributary sub-basins, specifically Town Cove, Pear Tree Cove, and Tiah Cove are all showing moderate-high levels of impairment related to their elevated chlorophyll-a levels and periodic oxygen depletions to levels stressful to estuarine animals living within the sediments. Similarly, Deep Bottom/Thumb Cove and the main basin of the great pond are generally showing a moderate level of impaired benthic habitat. While the species numbers and numbers of individuals remain high throughout the system, the community diversity and Evenness within each of the more impaired coves is low and indicative of a community under ecological stress. In all cases, these basins support communities with low diversity, with the measured index only 1.44 to 1.82. Evenness (how individuals are distributed among the species) was similarly low, 0.35 to 0.49 and indicated that only a few species were accounting for most of the individuals within each basin. The main basin and Deep Bottom/Thumb Cove are slightly better, but are still clearly showing moderately impaired relative to benthic animal habitat, with diversity indices of 2.0 to 2.3 and Evenness of 0.49 to 0.54. Only Black Point Pond is present supporting high quality benthic animal habitat, with diversity indices of 2.8 Evenness of 0.72. Equally important, this pond is part of a wetland system, serving as the central pond basin within a wetland system. As such this basin is naturally organic matter and nutrient enriched and the benthic communities have evolved to thrive within the wetland pond environment. The dominant species are not indicative of stress, but are tolerant of wetland conditions (*Streblospio, Mediomastus, Hypaniola and Leitoscoloplos*). In contrast, only the moderate organic enrichment indicators (*Streblospio, Mediomastus*) comprised generally three-quarters of the community within the coves. While typical of naturally organic rich wetland systems, these species do not dominate unimpaired open water embayments and their extreme dominance (~75% of community) is clear evidence of organic matter enrichment and in the Coves of Tisbury Great Pond, this results from nitrogen enrichment (due to watershed loading and limited tidal flushing). The main basin of Tisbury Great Pond showed greater diversity and a lower proportion (~50%) of the community represented by the moderate organic enrichment indicators (*Streblospio, Mediomastus*). However, there were also large numbers of crustaceans and molluscs, including some economic species (Mya) at some sites and also head down deposit feeders (e.g. *Pectinaria*). However, given the prevalence of organic enrichment indicator species it is clear that the main basin of Tisbury Great Pond is above its nitrogen threshold and is supporting moderately impaired benthic animal habitat.

The results of the infauna survey and complete loss of eelgrass coverage within the Tisbury Great Pond Embayment System indicates that the nitrogen management threshold analysis (Section VIII) needs to aim for lowering nitrogen enrichment for restoration of eelgrass habitat within the lower portion of the main basin and restoring infaunal habitat in the tributary coves showing moderate-high impairment of benthic habitat. However, it is important to note that in general the Tisbury Great Pond Embayment System is supportive of infauna habitat near its loading threshold, which should mean that only limited reductions in nitrogen enrichment is required for restoration. It should be emphasized that reducing nitrogen enrichment can be achieved by reducing nitrogen inputs and/or increasing its rate of loss through tidal exchange.

It is clear that the habitat impairments within the Tisbury Great Pond Embayment System are associated with nitrogen enrichment. The loss of the historical eelgrass makes restoration of this resource the primary focus for nitrogen management. Secondarily, the sub-basins that have slightly impaired benthic habitat should be restored as a consequence of management to restore the eelgrass habitat. Restoring these habitats should be the focus of the nitrogen management threshold analysis (Section VIII).

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth and available to the MEP Technical Team. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the propagation of shellfish (Figure VII-17). As is the case with some systems on Cape Cod, the majority of the enclosed waters of the Tisbury Great Pond system is approved for the taking of shellfish year round. A small section of the pond where Town Cove joins the main lower basin of the system is conditionally approved to shellfishing during specific times during the year, typically the cold winter months, indicating the system is generally supportive of shellfish communities. However, in the upper most reaches of the system, specifically Town Cove and Black Point Pond, harvest of shellfish is prohibited year round indicating the presence of a persistent environmental contaminant. In the case of the Town Cove closure, that is potentially due to bacterial contamination most likely from wildlife and surface water inflows. The closure of Black Point Pond is likely due to bacterial contamination from wetland surfaces and natural fauna living on or around that tributary basin to the overall Pond system. The major shellfish species with potential habitat within the Tisbury Great Pond Estuary are mainly soft shelled clams (*Mya arenaria*) in shallower waters fringing the shore of the pond as well as the American Oyster in Deep Bottom Cove, Town Cove and Black Point Pond as well as the shallow water fringing the shore (Figure VII-18).

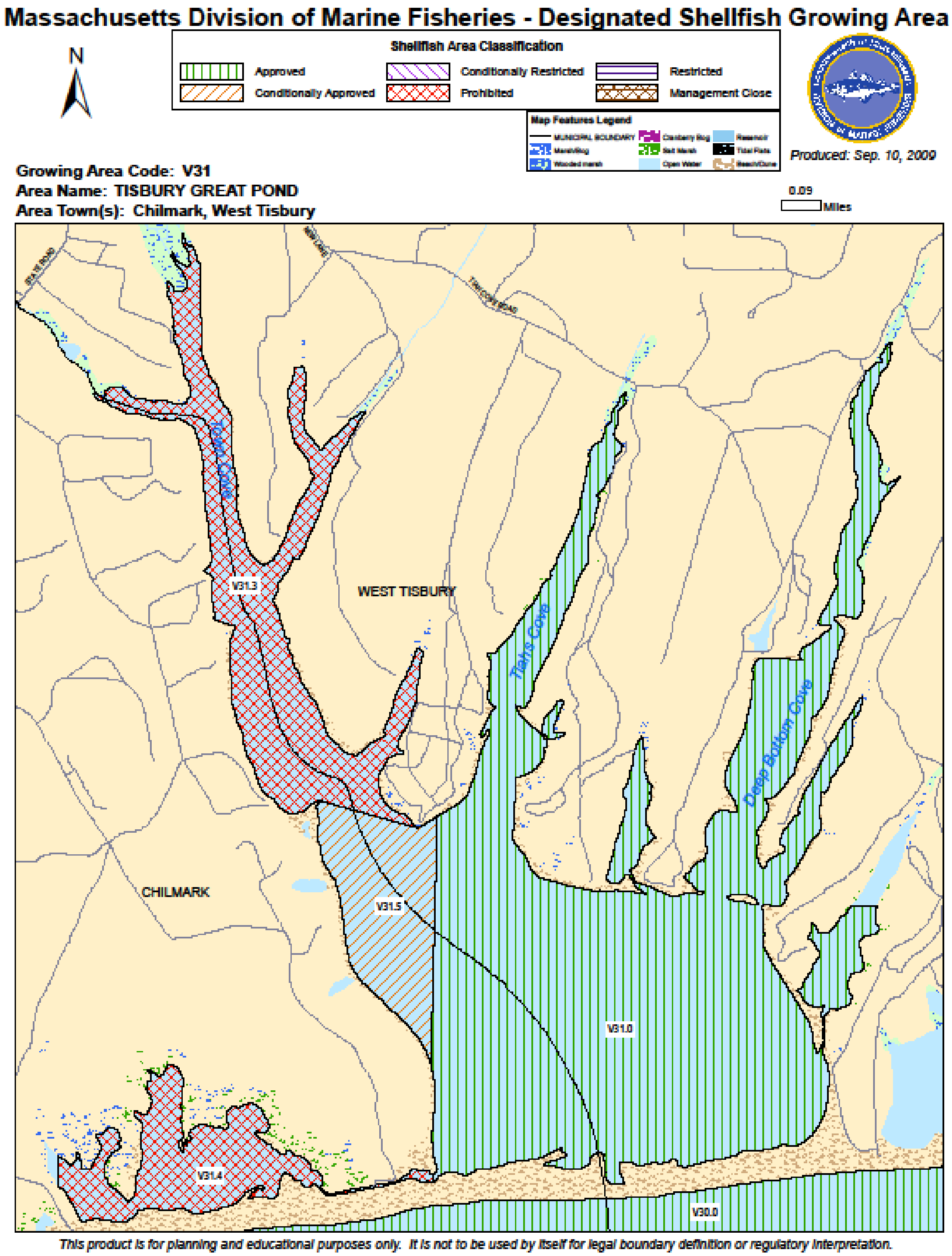

Figure VII-17. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

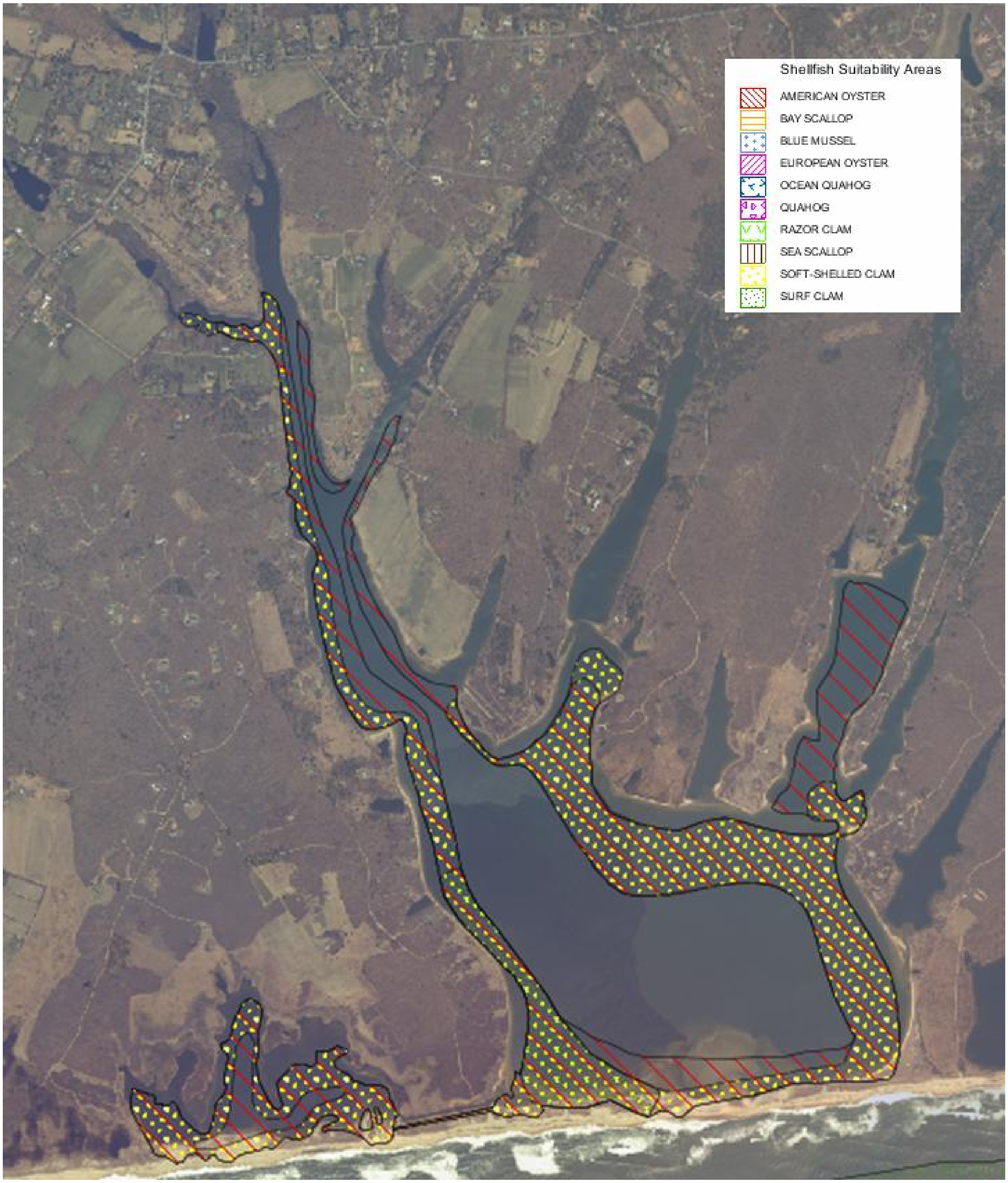

Figure VII-18. Location of shellfish suitability areas within the Tisbury Great Pond Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

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 and its watershed further strengthen the analysis. These data were collected to support threshold development for the Tisbury Great Pond Embayment System by the MEP Technical Team and were discussed in Section VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the long-term baseline Water Quality Monitoring Program conducted by the Towns of Chilmark and West Tisbury and the MV Commission, with technical guidance from the Coastal Systems Program at SMAST. The Tisbury Great Pond Embayment System is comprised of three major functional units, each with different levels of habitat quality. The main basin of Tisbury Great Pond (e.g. the lagoon formed by the barrier beach) is moderately to significantly impaired due to its complete loss of historic eelgrass coverage and has generally moderate impairment of its benthic animal habitat. The small tributary coves (Town Cove, Tiah Cove, Pear Tree Cove and Deep Bottom/Thumb Cove) are shallow narrow "fingers basins" to the main basin and all have moderate-significant impairment of benthic animal habitat and no historic eelgrass coverage. They are structurally and functionally similar and are the major initial receptors of watershed nitrogen inputs. The third unit, Black Point Pond, differs from the others as it functions as a shallow pond surrounded by wetlands (>40 acres), which likely persist due to the topography and relatively isolated hydraulic characteristics of the pond (restricted exchange through Crab Creek to the main basin). As a wetland influenced salt pond, Black Point Pond supports relatively high quality benthic animal habitat and has no evidence of supporting (historic or present) eelgrass habitat. Therefore there is a gradient in infaunal habitat quality, with the upper tributary coves showing greater impairment than the large lagoonal basin, and the generally isolated wetland Black Point Pond having the highest quality habitat.

Part of the MEP assessment of the Tisbury Great Pond Embayment System was confirmation that the critical parameter controlling habitat quality is nitrogen, hence managing nitrogen enrichment would result in restoration of observed impairments. Analysis of inorganic N/P molar ratios within the water column of the Tisbury Great Pond Embayment System are consistent with virtually all of the estuaries in southeastern Massachusetts and New England in that nitrogen is the critical nutrient to be managed. The measured Redfield Ratio (inorganic N/P) ranges from 2-7 within the main basin and coves of Tisbury Great Pond and 6 within Black Point Pond. These data and the low concentration of inorganic nitrogen (~0.014 mg L^{-1}) indicate that nitrogen additions will increase phytoplankton production, organic matter levels and turbidity within this system. Increased phytoplankton and organic matter levels increase oxygen consumption within the waters and sediments and increase the extent of oxygen depletion and habitat impairment. It should be noted that nitrogen enrichment occurs through two primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with low nitrogen offshore waters. Tisbury Great Pond has seen increasing nitrogen loading from its watershed from shifting land-uses and due to coastal processes along its barrier beach (it is only periodically opened to tidal exchange). Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs. Decreasing watershed nitrogen inputs or increasing tidal flushing will reduce nitrogen enrichment and its impacts. The present distribution and level of eelgrass and benthic animal habitat quality observed within the estuary is consistent with the degree of nitrogen enrichment, and its resulting increase in phytoplankton biomass, organic matter and oxygen levels. All of the habitat indicators are consistent with the above assessment of the whole of the Tisbury Great Pond Embayment System (Section VII).

Eelgrass: At present, eelgrass beds are not present in the Tisbury Great Pond Embayment System, although observations suggest that very small patches of eelgrass in the lower portion of the main basin near the barrier beach may occur after periods when the pond is open to tidal exchange for extended periods and anecdotal evidence supports the historical presence of eelgrass habitat under higher water quality conditions. The current lack of eelgrass beds is consistent with the elevated chlorophyll-*a* and low dissolved oxygen levels and watercolumn nitrogen concentrations within this system. That the historic eelgrass beds were restricted to the shallow margins versus within the "deeper" regions of the lower basin (1951) also indicates that nitrogen enrichment plays the key role in the distribution of eelgrass historically in this system and the absence of eelgrass at present.

Over the past several decades, eelgrass has generally not existed within the Tisbury Great Pond Embayment System. At the present moderate levels of watershed nitrogen loading with only periodic tidal exchange, the level of nitrogen enrichment has resulted in conditions no longer supportive of eelgrass (high chlorophyll, oxygen depletion, high turbidity). In addition, much of the system has structural impediments to supporting eelgrass even at moderate levels of nitrogen enrichment. The central region of the main basin and much of Deep Bottom and Town Coves are relatively deep requiring clearer waters (light penetration) than many shallow tidal estuaries within the region.

However, the MassDEP Eelgrass Mapping Program (C. Costello) along with supporting anecdotal evidence has determined that eelgrass did occur to some extent within Tisbury Great Pond historically (e.g. 1951). While the coverage identified could not be quantified relative to density or presence/absence of epiphytes, the southeastern side of the main basin between Tississa Pond and the barrier beach in waters generally 0.5 - 1.5 meters would be the area likely to have supported eelgrass. This pattern of distribution is consistent with information on historical eelgrass as obtained directly from a long time resident of West Tisbury with multi-decadal experience as a Pond Steward as well as working on Tisbury Great Pond at a time when shellfishing was a commercial venture on the Pond. Based on the MassDEP Eelgrass Mapping Program assessment of historical eelgrass in the Pond, if the bed were fully colonized by eelgrass it would represent a potential area of up to 50 acres. The region of the 1951 eelgrass bed presently contains the most consolidated sand containing sediments within this great pond, consistent with an area of habitat supportive of eelgrass. In addition, there possibly was a small patch of eelgrass (1951) to the west adjacent the barrier beach, likely associated with an historic area of elevated tidal flushing. The presence of eelgrass in this region is consistent with a low to moderately nitrogen enriched embayment system in 1951, with enrichment most likely due to the lack of tidal flushing. The absence of eelgrass in 1951 within the coves further supports this contention. The lack of eelgrass habitat in Black Point Pond is consistent with its depth and function as a wetland dominated basin.

The Tisbury Great Pond eelgrass coverage and temporal loss is similar to that in nearby Edgartown Great Pond. In Edgartown Great Pond, the 1951 eelgrass beds were limited to the lower main basin and no habitat was identified within the upper main basin and the numerous coves. However, some eelgrass has persisted and been observed in recent decades and in the MEP surveys of that system (particularly on the western shore of the main basin adjacent the barrier beach near the region of a historic tidal inlet), adding support for the 1951 coverages of both estuaries. The continuing presence of eelgrass in Edgartown versus Tisbury Great Pond is consistent with the lower chlorophyll-*a* and higher oxygen levels generally seen within Edgartown Great Pond. While it is not possible to determine the density of the eelgrass beds in 1951 within the main basin of Tisbury Great Pond, it does appear there was eelgrass habitat going back to the 1950's and 60's and that the coverage has declined to zero based on field observations conducted by the MEP Technical Team and others.

The loss of eelgrass beds within the main basin of Tisbury Great Pond relative to historical distribution (1951 photo interpretation and anecdotally supported) is expected given the measured levels of nitrogen enrichment and resulting chlorophyll-*a* and dissolved oxygen. Total nitrogen levels (TN) within the lower basin have mean summer time levels of 0.51 - 0.53 mg N L^{-1} compared to the levels in other similarly configured southeastern Massachusetts estuarine basins currently supporting eelgrass, 0.35-0.45 mg N L^{-1} (range of Cape Cod systems). Other key water quality indicators, dissolved oxygen and chlorophyll-*a*, show similar levels of moderate enrichment with periodic oxygen depletions below 5 mg/L and chlorophyll levels in blooms reaching 10-20 ug/l. While there is only a small gradient in nutrient related water quality parameters within this embayment system, the coves do generally support higher TN levels and larger phytoplankton blooms (chlorophyll-*a* averaging 15-20 ug L^{-1}, blooms 30-40 ug L^{-1}) and greater oxygen depletion. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, the lack of eelgrass habitat within the tributary Coves and the loss of eelgrass habitat within the main basin of Tisbury Great Pond is consistent with observed eelgrass habitat and areas of loss in numerous other estuaries throughout the region. The maximum areal loss of eelgrass coverage (1951 to present) within the lower main basin is potentially up to 50 acres, but the density cannot be fully quantified. This eelgrass loss combined with confirmation of its historical presence indicates that this basin is presently supporting significantly impaired eelgrass habitat and that restoration of this habitat should necessarily be part of nitrogen related restoration of the Tisbury Great Pond System. As mentioned in Chapter 7, based on modeling conducted as part of this effort, achieving the nitrogen threshold restorative of infaunal benthic habitat throughout the Tisbury Great Pond system as well as the nitrogen threshold specific to the main basin will result in the restoration of eelgrass habitat in those areas suggested by historical evidence. Also, nitrogen management for eelgrass and infauna habitat restoration will protect Black Point Pond from potential future nitrogen over-enrichment, either directly through management of nitrogen sources within the Black Point Pond watershed or through lower nitrogen concentrations in the adjacent main basin waters. While eelgrass habitat impairment is one major driver for management within the lower main basin of the Tisbury Great Pond Embayment System, the other is benthic animal habitat, a critical estuarine resource which is impaired within each of the tributary coves to the main basin. Benthic animal habitat does generally have a higher tolerance for nitrogen enrichment than eelgrass as benthic animals do not require light for growth and therefore higher levels of turbidity and phytoplankton biomass are tolerated. Infauna habitat quality is the primary indicator of the health of embayment basins that naturally do not support eelgrass and therefore are important in the management of the tributary basins to the main basin of Tisbury Great Pond.

Relative to setting a benchmark for eelgrass restoration, it is unfortunate that the density of the historical 1951 beds have not been quantified, however, as described in Section VII, anecdotal evidence was obtained that supports the MassDEP assessment and indicates that eelgrass habitat present in the 1950's and 60's was dense and that water clarity was noticeably higher than currently. These conditions existed despite the only periodic tidal exchange and therefore "naturally" nitrogen enriched condition of the Pond. Routine opening of this salt pond was initiated in the 1940's and would have been required for habitat maintenance at that time, as well as today, as nutrient levels in the Pond gradually increased to the levels observed presently. Based upon the 1951 eelgrass coverage data it appears that potentially up to 50 acres of eelgrass habitat might be restored if nitrogen management alternatives were implemented. Coupling restoration of eelgrass habitat within the lower basin to embayment-wide restoration of infaunal habitat should be used to set the nitrogen threshold for management of this salt pond.

Water Quality: Overall, Tisbury Great Pond and its tributary coves, exclusive of Black Point Pond, are presently showing a moderate to high level of habitat impairment (eelgrass and infaunal animals) resulting from summer oxygen depletion and organic enrichment primarily from phytoplankton production, parameters directly affected by nitrogen enrichment. The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a levels indicate moderately nutrient enriched waters and impaired habitat quality within the upper and lower basins. The oxygen data is consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-a. The periodic elevated oxygen levels observed in some of the Coves provides additional evidence that this system is presently receiving nitrogen inputs above the threshold required to maintain high quality estuarine habitat at its present rate of tidal exchange (Table VIII-1).

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a levels indicate moderately to highly nutrient enriched waters with higher nutrient related water quality in the main basin and Black Point Pond and greater levels of oxygen depletion and phytoplankton biomass in the Coves, such as Town Cove and Tiah Cove (Figures VII-3 through VII-14). It should be noted that the Water Quality Monitoring Program observed similar levels of chlorophyll-a and bottom water oxygen depletion in critical areas of the system, although these periodic samples did not always capture the minimum oxygen or maximum chlorophyll-a conditions at a given site. The measured levels of oxygen depletion and enhanced chlorophyll-a levels and are consistent with the nitrogen levels within the various basins (Section VI), and the parallel variation in these water quality parameters is consistent with watershed/tidal flushing based nitrogen enrichment of this estuarine system.

The oxygen records show that the inner sub-embayments of Tisbury Great Pond, specifically Town Cove and Tiah Cove, which receive significant watershed nitrogen loads relative to their volumes and turnover rates, have the largest daily oxygen excursions, a nutrient related response. The central region of Town Cove has clear evidence of oxygen levels above atmospheric equilibration providing additional documentation of potential impairment through nitrogen over-enrichment.

Measured dissolved oxygen depletion indicates that the sub-basins to the Tisbury Great Pond Embayment System, such as the Town Cove and Tiah Cove, and to a lesser extent the main lagoonal basin formed behind the barrier beach, show high to moderate levels of oxygen stress respectively, as does bottom water oxygen data from the monitoring program (1995-2010). The largest oxygen depletions and excursions were observed in Town Cove, which receives large quantities of groundwater and surface water transported nutrient load from the watershed. The observed spatial pattern indicated that the level of oxygen depletion (Table VII-1), chlorophyll-a (Table VII-2) and total nitrogen levels increased with increasing distance from the tidal inlet, periodically created through the barrier beach. This temporary inlet opening serves to lower pond and associated groundwater levels, but also provides the most promising mechanism for restoration of pond habitats presently impaired due to nitrogen enrichment by exchanging nitrogen and organic matter enriched pond waters with high quality waters of the Atlantic Ocean. The Water Quality Monitoring Program results are consistent with the MEP time-series data, indicating nitrogen enrichment depending on the location overall pond system, with higher nitrogen levels in the Coves and moderate levels in the main basin of Tisbury Great Pond. Measured bottom water oxygen depletion followed this same pattern as did the gradient in chlorophyll.

The relatively uniform level of moderate-significant infauna habitat impairment in the Coves and moderate impairment within the main basin is consistent with the small range in observed total nitrogen levels throughout this estuary, 0.51 mg N L^{-1} in the lower basin to 0.54 mg N L^{-1} in the Coves, with only the uppermost region of Town Cove (near the surface water inflows) reaching 0.56-0.64 mg N L^{-1}. The relative uniformity of total nitrogen results from the non-tidal nature of this system, the few major surface water discharges (only upper Town Cove) and the absence of major restrictions. As discussed below, these levels of water column TN during summer have been documented to cause moderate to high (0.5 - 0.6 mg N L^{-1}) impairment of infaunal animal communities in southeastern Massachusetts estuaries. The pattern of oxygen depletion, elevated chlorophyll-a and nitrogen levels are consistent with the present lack of eelgrass and the quality of infaunal habitats (Section VII.4) throughout the Tisbury Great Pond Embayment System. These assessments indicate an estuarine system that is beyond its ability to assimilate nitrogen loads without impairment.

Infaunal Communities: Overall, the infauna survey indicated that most sub-basins comprising the Tisbury Great Pond Embayment System are presently beyond their ability to tolerate additional nitrogen inputs without impairment. The exception is Black Point Pond which is functionally a wetland basin (e.g. a pond surrounded by significant wetland area). There was a clear spatial pattern in habitat quality, with moderately to significantly impaired benthic animal habitat found in the upper tributary coves and moderately impaired areas within the large main basin (and as noted, Black Point Pond). The Benthic Survey did not reveal any areas of severe degradation, as indicated by low numbers of individuals and species or dominance by opportunistic stress indicator species (such as Capitellids and Tubificids). In fact, at all locations throughout the sub-basins of this embayment system, there were high numbers of individual (>600 per grab sample), moderate to high numbers of species (14 to 20 per sample) and low numbers of Capitellids and Tubificids (generally <10% of community). Species numbers of 20-25 generally indicate high quality benthic habitats. While there is little evidence of severe nitrogen related impairment of benthic animal communities, most areas clearly showed evidence of moderate impairment associated with nitrogen and organic matter enrichment.

The upper tributary sub-basins, specifically Town Cove, Pear Tree Cove, Tiah Cove are all showing moderate-high levels of impairment related to their elevated chlorophyll-a levels and periodic oxygen depletions to levels stressful to estuarine animals living within the sediments. Similarly, Deep Bottom/Thumb Cove and the main basin of the great pond are generally showing a moderate level of impaired benthic habitat. While the species numbers and numbers of individuals remain high throughout the system, the community diversity and Evenness within each of the more impaired coves is low and indicative of a community under ecological stress. In all cases, these basins support communities with low diversity (1.44 to 1.82, Table VII-4). Evenness (how individuals are distributed among the species) was similarly low, 0.35 to 0.49 and indicated that only a few species were accounting for most of the individuals within each basin. The main basin and Deep Bottom/Thumb Cove are slightly better, but are still clearly moderately impaired, with diversity indices of 2.0 to 2.3 and Evenness of 0.49 to 0.54. Only Black Point Pond is presently supporting high quality benthic animal habitat, with diversity indices of 2.8 Evenness of 0.72. Equally important, this pond is part of a wetland system, serving as the central pond basin (~60 acres) with extensive fringing wetlands (>40 acres). As such this basin is naturally organic matter and nutrient enriched and the benthic communities have evolved to thrive within the wetland pond environment. The dominant species are not indicative of stress, but are tolerant of wetland conditions (*Streblospio, Mediomastus, Hypaniola and Leitoscoloplos*). In contrast, only the moderate organic enrichment indicators (*Streblospio, Mediomastus*) comprised generally three-quarters of the community within the coves. While typical of naturally organic rich wetland systems, these species do not dominate unimpaired open water embayments and their extreme dominance (~75% of community) is clear evidence of organic matter enrichment and in the Coves of Tisbury Great Pond, this results from nitrogen enrichment (due to watershed loading and limited tidal flushing). The main basin of Tisbury Great Pond showed greater diversity and a lower proportion (~50%) of the community represented by the moderate organic enrichment indicators (*Streblospio, Mediomastus*). However, there were also large numbers of crustaceans and mollusks, including some economic species (Mya) at some sites and also head down deposit feeders (e.g. *Pectinaria*). However, given the prevalence of organic enrichment indicator species it is clear that the main basin of Tisbury Great Pond is above its nitrogen threshold and is supporting moderately impaired benthic animal habitat. Similarly, the tributary Coves, with higher nitrogen levels than the main basin are showing greater impairment of benthic animal habitat consistent with the moderate to high levels of chlorophyll-a, organic matter enrichment and oxygen depletion (Table VIII-1).

Overall, the infaunal habitat quality was consistent with the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily included the structure of the specific estuarine basin. Based upon this analysis it is clear that the tributary Coves are presently supporting moderately to significantly impaired benthic habitat while the main basin generally shows moderate quality. Black Point Pond, as a functioning wetland influenced pond, currently retains high habitat quality. Impairment in the Coves and main basin is through nitrogen and organic matter enrichment. The results of the water quality and benthic animal assessments (Table VIII-1) and the complete loss of eelgrass coverage within the Tisbury Great Pond Embayment System, indicates that the nitrogen management threshold analysis (Section VIII.2) needs to aim for lowering nitrogen levels for restoration of eelgrass habitat within the lower portion of the main basin and for restoring infaunal habitat in the tributary coves. However, it is important to note that in general the Tisbury Great Pond Embayment System is supportive of infauna habitat above, but close to, its loading threshold, which should mean that only limited reductions in the level of nitrogen enrichment should be required for restoration. Therefore, lowering nitrogen levels within the main basin for eelgrass restoration should result in restoration of the benthic animal habitat, as well. It should be emphasized that reducing nitrogen enrichment can be achieved by reducing nitrogen inputs and/or increasing its rate of loss in tidal exchange.

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout an embayment system, is to first identify the critical spatial distribution and second to determine the nitrogen concentration within the water column which will restore those locations to the desired habitat quality. The sentinel location(s) are selected such that their restoration will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site(s) and the target nitrogen level are determined, the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Tisbury Great Pond Embayment System (Towns of Chilmark and West Tisbury, MA.), based upon assessment data presented in Section VII. The main basin of Tisbury Great Pond and its major tributary sub-embayments (Coves, Black Point Pond) only have periodic tidal exchange with ocean waters during managed breaching of the barrier beach, as a result. Some basins were approximated using water quality monitoring data coupled with instrument mooring data (D.O., chlorophyll-a). WQMP refers to water quality monitoring program.

	Tisbury Great Pond Embayment System						
	Main Basin		Tributary Coves				
Health Indicator	**Upper[1]**	**Lower**	**Town Cove**	**Pear Tree Cove**	**Tiah Cove**	**Deep Bottom Cove [a]**	**Black Point Pond**
Dissolved Oxygen	MI[2]	H-MI[3]	SI[4]	MI[5]	MI-SI[6]	H-MI[7]	--[8]
Chlorophyll	MI-SI[9]	MI[10]	MI-SI[11]	MI[12]	SI[13]	MI-SI[14]	H[15]
Macroalgae	--[16]	--[16]	--[16]	--[16]	--[16]	--[16]	--[16]
Eelgrass	--[17]	MI-SI[18]	--[17]	--[17]	--[17]	--[17]	--[17]
Infaunal Animals	MI-SI[19]	MI[20]	MI-SI[19]	MI-SI[19]	MI-SI[19]	MI-SI[19]	H[21]
Overall:	**MI-SI[22]**	**MI-SI[23]**	**MI-SI[22]**	**MI-SI[22]**	**MI-SI[22]**	**MI-SI[22]**	**H[24]**

a -- Thumb Cove and Deep Bottom Cove were combined for assessment
1 -- integration of moored instrument (3) results and WQMP data, as appropriate.
2 – oxygen levels at mouth of Town Cove frequently >4 mg/L (23% record), with periodic depletions to <2 mg/L.; lower basin southeast periodically <4 mg/L and west >6 mg/L 90% of record.
3 – southwest mooring, oxygen levels generally >6 mg/L (90% of record) and WQMP >6 mg/L; southeast mooring, >5 mg/L, 80% or record, periodic diurnal declines to <3 mg/L.
4 – mid & lower mooring frequently <4 mg/L (14%-23% of record), <3 mg/L (7%-11%) periodically to 1 mg/L; WQMP periodically <4 mg/L and <3 mg/L (4% of samples). Frequent levels >10 mg/L indicate nitrogen enrichment and eutrophication. Deep basin.
5 -- WQMP frequently <5 mg/L and periodically <4 mg/L (5% of samples), shallow basin.
6 – oxygen depletions frequently to <5 mg/L (26% of record), <4 mg/L 11% or record, periodically to 2 mg/L.
7 – oxygen >5 mg/L (88% of record), rarely to >4 mg/L (2% of record and 2% of WQMP samples)
8 -- insufficient data for assessment on this Health Indicator
9 – moderate chlorophyll-a levels, average 12 ug/L, with periodic blooms to 25 ug/L; WQMP average ~10 ug/L with blooms to ~30 ug/L.
10 – moderate chlorophyll-a levels, average 11 ug/L, with blooms typically 15-20 ug/L; WQMP average ~9 ug/L., with periodic blooms typically 15-20 ug/L
11 – moderate-high chlorophyll-a levels, average 12-15 ug/L, frequently >20 ug/L (11%-22% of record), with blooms >30 ug/L; WQMP average 10-16 ug/L., with periodic blooms >30 ug/L
12 – moderate chlorophyll-a levels, WQMP average 12 ug/L, with periodic blooms typically 15- 20 ug/L
13 – high chlorophyll-a levels, average 27 ug/L, frequently >40 ug/L, with blooms >50 ug/L
14 – moderate-high chlorophyll-a levels, average 19 ug/L, frequently >20 ug/L (38% of record), blooms >30 ug/L; WQMP average ~10 ug/L., with periodic blooms >30 ug/L
15 – low-moderate chlorophyll-a levels, WQMP average 5 ug/L, with maximum 13 ug/L.
16 -- drift algae sparse or absent, little surface microphyte mat, no visible accumulations
17 – no evidence this basin is supportive of eelgrass.
18 -- eelgrass beds (1951); now very sparse eelgrass periodically appearing in lowermost main basin (2009), not observed in MEP surveys. Major eelgrass loss, but density of beds unquantified indicates moderate-significant impairment
19 – High numbers of individuals (600-2000), moderate species numbers (14-18), low diversity (1.4-2.0) and Evenness (0.35 to 0.52). Dominated by organic and nitrogen enrichment indicators (*Streblospio, Mediomastus*) comprising >75% of community.
20 – High numbers of individuals (>1000), moderate-high species numbers (20), low-moderate diversity (2.3) and Evenness (0.54). Dominants include organic and nitrogen enrichment indicators (*Streblospio, Mediomastus*) comprising ~50% of community, but amphipods & other crustaceans & molluscs, some head down deposit feeders. Sediments have oxidized surface layer and bioturbation.
21 – High numbers of individuals (>600), moderate numbers of species (15), with high diversity (2.8) and Evenness (>0.7). Benthic community is consistent with high quality habitat in a wetland basin.
22 -- no historic eelgrass, assessment based on impairment of benthic communities showing moderate-significant impairment as evidenced by moderate number of species, low diversity & Evenness, with clear dominance by 2 organic enrichment tolerant species consistent with periodic oxygen depletion and high phytoplankton biomass. Nitrogen management to restore this key resource should be undertaken.
23 -- eelgrass has been lost since 1951, density unquantified; indicates moderate-significant impairment of this basin. Note that benthic animal habitat is moderately impaired as evidenced by the dominance of organic enrichment indicator species, low diversity and Evenness and periodic oxygen depletion. Nitrogen management to restore these key habitat types should be undertaken.
24 – Habitat indicators consistent with an unimpaired wetland influenced basin.

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

Since the Tisbury Great Pond System does not support strong horizontal gradients (range in total nitrogen levels from 0.51 mg N L^{-1} in the main basin to 0.54 in the coves[3], the higher uppermost Town Cove levels are associated with the surface water inflows), it was determined to use the average of long-term water quality stations to determine the nitrogen within the main basin relative to restoration of eelgrass (TGP 7) and benthic habitat in the tributary Cove stations (TGP 4,5,6). This distributed "location" for the threshold stems from the variability at individual sites and the non-tidal nature of this system. The stations associated with the main basin (TGP-4 & 7) are presently showing an average TN level of 0.519 mg N L^{-1}. As noted in previous sections the average concentrations at these stations approximate concentrations throughout the pond waters (i.e. are representative of other pond locations).

Relative to setting a benchmark for restoration, it is unfortunate that the density of the historical, 1951, beds have not been quantified, however, that dense beds existed despite only periodic opening to tidal exchange and "naturally" nitrogen enriched condition has been anecdotally confirmed and helps support the MEP nitrogen threshold. Routine opening of this salt pond was initiated in the 1940's and would have been required for habitat maintenance at that time, as well as today. Therefore, habitat restoration in this nutrient enriched system should focus on improving eelgrass habitat within the lower main basin, as well as full restoration of infaunal habitat quality, pond-wide. It should be noted that there is no evidence of eelgrass habitat within the upper main basin or within the major tributary coves. Although Black Point Pond is presently not showing impaired benthic animal habitat, lowering nitrogen levels for restoration of Tisbury Great Pond will serve to protect this wetland influenced tributary basin.

The results indicate that eelgrass has been lost from the main basin of Tisbury Great Pond in areas that presently support averaged TN levels of 0.51-0.53 mg N L^{-1}. Upwards of 50 acres of eelgrass has been lost since 1951, as determined by the MassDEP Eelgrass Mapping Program. The prior eelgrass was restricted to shallow water, 0.5 - 1.5 meters, most likely due to the systems natural enrichment of nitrogen from the lack of continuous tidal exchange. Based upon comparison to other regional estuaries the MEP Technical Team determined that lowering the nitrogen level within the main basin to 0.46 mg N L^{-1} would be supportive of sparse eelgrass in the shallow margins within the main basin of Tisbury Great Pond. This is based in part on the fact that eelgrass has not been present within this system for decades and present TN levels are causing impairment of this resource. In addition, this level is comparable to other estuaries with eelgrass restricted to shallow water areas. Depth is important in setting a threshold for eelgrass as deeper beds require more light penetration (lower TN) than shallow areas. These TN levels are higher than generally found in high quality eelgrass habitat in deeper systems (>2 m) like Stage Harbor (0.38 mg L-1) or West Falmouth Harbor and Phinneys Harbor (0.35 mg L^{-1}). However, in shallow water systems eelgrass beds are sustainable at higher tidally averaged TN levels. It should be noted that the historic Tisbury Great Pond eelgrass habitat was found mainly within shallow waters, consistent with the MassDEP Eelgrass Mapping Program assessment of this system. Systems like the Bournes Pond Estuary, where eelgrass has historically been confined to the lower estuarine basin, has nitrogen concentrations supportive of eelgrass at 0.45 mg TN L^{-1} within the main stem of the channel to the upper estuary, with a lower level, 0.42 mg TN L^{-1}, within the open water basin of Israel's Cove. The higher threshold within the main channel region of the Bournes Pond system is supported by the existence of healthy eelgrass beds at tidally averaged TN concentrations of 0.426 mg TN L^{-1} and the presence of eelgrass in patches (not beds) at tidally averaged TN of 0.481 mg TN L^{-1}. Similarly, in the shallow eelgrass areas within the Westport River Estuary, high quality eelgrass

[3] The higher TN levels in the uppermost region of Town Cove (0.56-0.64 mg N L^{-1}) were primarily associated with initial region of the river discharges.

habitat presently exists at TN levels greater than 0.43 mg N L^{-1}, but less than 0.48 mg N L^{-1}. The threshold tidally averaged TN level for restoration of eelgrass is within the shallow margins of the main basin of Tisbury Great Pond (0.46 mg TN L^{-1}) where light reaches the sediments at higher TN levels than in deeper areas. It should be noted that the threshold is slightly higher than that for Bournes Pond, as it has dense fringing beds, while only sparse beds can be targeted for Tisbury Great Pond based on available information.

Since the infaunal community at all sites within the Coves and main basin of Tisbury Great Pond are supporting low diversity communities with large numbers of organic matter enrichment tolerant species, comparisons to other estuarine systems in the MEP region were relied upon. In numerous estuaries it has been previously determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat. This level was found for Popponesset Bay where based upon the infaunal analysis and parallel nitrogen data (measured and modeled), nitrogen levels on the order of 0.4 to 0.5 mg TN L^{-1} were found supportive of high infaunal habitat quality in this system. Similarly, in the deeper basins of Three Bays System, healthy infaunal areas are found at nitrogen levels of TN <0.42 mg TN L^{-1} (Cotuit Bay and West Bay) and in Eel Pond (Bourne) at a TN level of 0.45 mg TN L^{-1}. Conversely, moderate impairment of infaunal habitat has routinely been documented by the MEP in areas with nitrogen levels of TN >0.5 mg TN L^{-1}. For example, the moderately impaired infaunal habitat in Hyannis Inner Harbor (Barnstable) at 0.518-0.574 mg TN L^{-1}, in Bournes Pond and Great Pond (Falmouth) at >0.6 mg TN L^{-1}. Relative to Tisbury Great Pond, benthic habitat is presently impaired at nitrogen levels generally 0.51-0.54 mg TN L^{-1}. However, it appears that Tisbury Great Pond is presently just above its nitrogen enrichment threshold, so a threshold level of 0.48 mg TN L^{-1} is more appropriate relative to conditions within this nitrogen sensitive basin. This threshold nitrogen level represents the secondary threshold relative to benthic animal habitat and should be attained if the primary threshold, which is set based upon eelgrass, is met. The slightly lower threshold for Tisbury Great Pond compared to the noted much larger open tidal systems is consistent with the greater fraction of in situ production deposited (organic enrichment) within the Tisbury Pond basins than those in systems fully open to tidal exchange.

The integration of all information available clearly supports a nitrogen threshold for restoration of sparse eelgrass habitat within the main basin of Tisbury Great Pond of 0.46 mg N L^{-1} and a target nitrogen threshold for healthy infaunal habitat within the tributary Coves of 0.48 mg N L^{-1} (time averaged). The modeling simulations in Section VIII-3 show that if a time averaged 0.48 mg/L threshold concentration is met at Stations TGP-4,5 and 6 and a threshold concentration of 0.46 mg/L is met at Station TGP-7 , then conditions for restoration of benthic habitat in the upper basin and restoration of eelgrass habitat in the lower basin, to the extent at which it historically existed, would be achieved. This significant lowering of average TN levels within the lower basin of Tisbury Great Pond will also simultaneously improve benthic animals throughout this embayment system. As the threshold nitrogen level is lower than present conditions watershed management should focus on keeping future build-out nitrogen loads below levels that would result in nitrogen levels at the sentinel station from exceeding the threshold (Section VIII.3).

VIII.3 DEVELOPMENT OF TARGET NITROGEN LOADS

After developing the dispersion-mass balance model of Tisbury Great Pond to simulate conditions that exist as a result of present management practices, the model was used to simulate a modified management approach that could be followed to improve water quality conditions in the pond year-round.

With a goal of seeking further improvements in water quality conditions in the Pond, an alternate management scheme was modeled using the previously developed dispersion-mass balance model. The two main goals of this threshold load and inlet opening scenario were to restore benthic infauna habitat throughout Tisbury Great Pond and simultaneously restore a modest level of eelgrass habitat within the southeastern and southwestern areas of the main basin. To restore benthic habitat, load reduction focused on lowering average TN levels of stations TGP 4, TGP 5 and TGP 6 to 0.48 mg/L during the summer months, when benthic regeneration and algae production is greatest. To restore a modest level of eelgrass habitat (consistent with the uncertainties in the historic distribution), the management scenario also focused on lowering of time-averaged TN concentrations in the lower main basin of the pond to 0.46 mg/L (at monitoring station TGP 7) over the same period. Both goals were achieved by reducing the watershed loading to the pond, together with an additional mid-summer breach. Watershed loading was reduced from present conditions until the combined time averaged TN concentration would remain below 0.48 mg/L across stations TGP 4, TGP 5 and TGP 6 and below 0.46 mg/L for station TGP 7, during a 100-day period, from the end of May to mid-September. The threshold modeling assumptions include 1) a successful late spring breach, which lowers the average pond TN concentration to 0.30 mg/L; 2) a successful mid-summer breach that remains open for 17-days, and which again lowers pond-averaged TN concentrations to 0.30 mg/L. The Pond is also allowed to be closed for 60 days, which is the time required for the water level in the model to rise to 3.7 feet NAVD (using average groundwater/surface water discharge rates and beach flow-through loss as discussed in Section VI). It should be noted that both restoration goals were met with a single scenario, so that either target yields requires the same watershed load reduction and additional inlet opening. This has occurred in other MEP threshold analyses for other estuaries, where when the eelgrass threshold is achieved, the restoration threshold for the impaired areas of benthic habitat are also achieved.

The resulting threshold septic loading is presented in Table VIII-2. A 54% septic reduction from present conditions together with a breach duration of 17 days was required in the septic load to the pond to achieve the threshold requirements. In this scenario 80% of the septic load is removed from the Great Pond main watershed, while 70% of the total septic load is removed from both the Tiasquam River watershed and Mill Brook watershed. All other watershed sources, including agricultural loads, were not reduced for this scenario.

This septic load change results in a 25.3% change in the total watershed load to the pond, as shown in Table VIII-3. A tabulation of all the loads to the pond is provided in Table VIII-4. The benthic loading term is effected by the change in watershed load. The method described in section VI.2.5.1 was used to adjust the benthic regeneration load to the pond for threshold conditions.

Table VIII-2. Comparison of sub-embayment septic loads used for modeling of present and modeled threshold loading scenarios of Tisbury Great Pond. 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 (kg/day)	threshold change
Deep Bottom Cove	1.233	1.233	*0.0%*
Tiah Cove	1.137	1.137	*0.0%*
Pear Tree Cove	1.699	1.699	*0.0%*
Tisbury Great Pond main basin	6.408	1.282	*-80.0%*
Black Point Pond	0.447	0.447	*0.0%*
Mill Brook (freshwater)	2.301	0.690	*-70.0%*
Tiasquam River (freshwater)	2.921	0.876	*-70.0%*
Total	16.145	7.363	*-54.4%*

Table VIII-3. Comparison of sub-embayment watershed loads used for modeling of present and modeled threshold loading scenarios of Tisbury Great Pond. 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 (kg/day)	threshold change
Deep Bottom Cove	2.803	2.803	*0.0%*
Tiah Cove	2.247	2.247	*0.0%*
Pear Tree Cove	3.836	3.836	*0.0%*
Tisbury Great Pond main basin	22.096	16.969	*-29.0%*
Black Point Pond	0.800	0.800	*0.0%*
Mill Brook (freshwater)	8.644	7.033	*-26.6%*
Tiasquam River (freshwater)	5.556	3.512	*-52.6%*
Total	45.981	37.199	*-25.3%*

Table VIII-4. Sub-embayment and surface water loads used for total nitrogen modeling of threshold conditions for Tisbury Great Pond, 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)
Deep Bottom Cove	2.803	1.507	0.550
Tiah Cove	2.247	0.775	-1.338
Pear Tree Cove	3.836	0.258	0.007
Tisbury Great Pond main basin	16.969	7.830	8.901
Black Point Pond	0.800	0.926	6.170
Mill Brook (freshwater)	7.033	-	-
Tiasquam River (freshwater)	3.512	-	-
Total	37.199	11.296	14.289

The effect on TN concentrations through the course of the summer of the threshold management scenario suggested for Tisbury Great Pond is presented in Figure VIII-1. For the 100-day period shown in Figure VIII-1, the time averaged TN concentration is 0.46 mg/L. The average concentration of TGP 4 (Town Cove), TGP 5 (Tiah Cove) and TGP 6 (Deep Bottom Cove) for this same time period is 0.48 mg/L, which achieves the TN level currently supportive of unimpaired benthic habitat in this system.

It is important to note that the threshold scenario provided as part of this report is one of many possible loading and breaching combinations that could work to improve water quality in the Pond. If the inlet could be opened reliably for a period longer than 17 days, the threshold concentration could likely be achieved with less watershed load reduction.

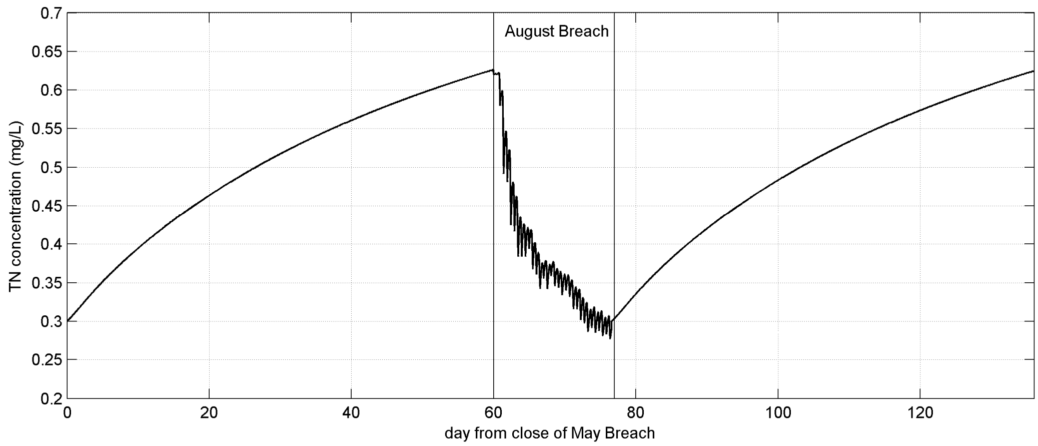

Figure VIII-1. Time series of modeled TN concentrations at monitoring station TGP 7 from the threshold model scenario where the pond is breached in late May and again in late July.

IX. REFERENCES

Anderson Nichols & Co., Edgartown Water Resource Protection Program (1984)

Brigham Young University (1998). "User's Manual, Surfacewater Modeling System."

Cambareri, T.C. and E.M. Eichner. 1993. Hydrogeologic and Hydrochemical Assessment of the Brewster Landfill (Brewster, Massachusetts). Cape Cod Commission and Barnstable County Department of Health, Human Services, and the Environment, Barnstable, MA.

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

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

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

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

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

Delaney, D.F. 1980. Ground-Water Hydrology of Martha's Vineyard, Massachusetts. US Geological Survey Hydrologic Investigations Atlas HA-618.

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

Earth Tech (1998) Preliminary Data: Meeting House Golf LLC

Earth Tech Inc., Groundwater Modeling for the Delineation of the Watershed to Edgartown Great Pond.

ESS Group. 2012. Final Report Engineering and Environmental Studies for the Mill Pond. Prepared for: Town of West Tisbury. East Providence, RI.

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

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

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

Fugro-McClelland East, Inc. 1992. Water Quality Study of Tisbury Great Pond. Prepared for the Towns of West Tisbury and Chilmark. Sandwich, MA.

Gaines, A. 1993, Coastal Resources Planning and Management: Edgartown Great Pond. WHOI, Woods Hole, MA

Gaines, A. 1995. Managing Domestic Wastewater at the Coast: A Natural Systems Assessment of Sengekontacket Pond, Martha's Vineyard. Prepared for Friends of Sengekontacket, Inc. Marine Policy Center, Woods Hole Oceanographic Institution.

Gaines, A. (1996) An Artificial Inlet for Application on a Seasonally High Energy Barrier Beach. Proposal to Boldwater Homeowners by Coast & Harbor Consultants

Healy, Kent. 2009. The Hydrology of Tisbury Great Pond, Martha's Vineyard, Massachusetts. (Un-published)

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

Howes, B.L. and C.T. Taylor. 1990. Nutrient Regime of New Bedford Outer Harbor: Infaunal Community Structure and the Significance of Sediment Nutrient Regeneration to Water Column Nutrient Loading. Final Technical Report to Camp, Dresser and McKee, Boston, Mass. for the City of New Bedford, Mass. and EPA. 140 pp.

Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, J. Wood, E. Eichner (2004). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Popponesset Bay, Mashpee and Barnstable, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2003). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Stage Harbor, Sulphur Springs, Taylors Pond, Bassing Harbor and Muddy Creek, Chatham, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Three Bays, Barnstable, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B.L., J.S. Ramsey, R.I. Samimy, D.R. Schlezinger, E.M. Eichner. 2007. Linked Watershed-Embayment Model to Determine the Critical Nitrogen Loading Threshold for the Edgartown Great Pond System, Edgartown, Massachusetts. SMAST/MassDEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B., H.E. Ruthven, E.M. Eichner, J.S. Ramsey, R.I Samimy, D.R. Schlezinger (2007). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Lewis Bay System, Towns of Barnstable and Yarmouth, MA. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Horsley & Witten Inc, Herring Creek Farm Study

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

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

Llewellyn-Smith, The Hydrogeology of Martha's Vineyard, Mass. MS Thesis, UMASS Dept. Geology and Geography, 1987.

Main Engineers, Geohydrologic Study For the Edgartown Water Pollution Control Facility (1986)

Martha's Vineyard Commission (1998) Data Report, Dukes County, MA. 1998

MV Commission (2005) Martha's Vineyard Watershed Land Use Analysis: Lagoon Tashmoo and Sengekontacket Ponds.

Massachusetts Division of Water pollution Control (1977) Martha's Vineyard Water Quality Study

Massachusetts Department of Environmental Protection. 1999. DEP Nitrogen Loading Computer Model Guidance. Bureau of Resource Protection. Boston, MA. Available at: http://www.state.ma.us/dep/brp/dws/techtool.htm

Massachusetts Department of Revenue. November, 2002. Property Type Classification Codes.

Massachusetts Department of Revenue. 2009. Property Type Classification Codes, Non-arm's Length Codes and Sales Report Spreadsheet Specifications. Prepared by the Bureau of Local Assessment. Revised June, 2009. Boston, MA.

Masterson, J.P. and P.M. Barlow. 1996. Effects of simulated ground-water pumping and recharge on ground-water flow in Cape Cod, Martha's Vineyard, and Nantucket Island Basins, Massachusetts. U.S. Geological Survey Water-Supply Paper 2447.

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

Millham, N.P. and B.L. Howes, (1994a). Freshwater flow into a coastal embayment: groundwater and surface water inputs. Limnology and Oceanography 39: 1928-1944.

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

Norton, W.R., I.P. King and G.T. Orlob (1973). "A Finite Element Model for Lower Granite Reservoir", prepared for the Walla Walla District, U.S. Army Corps of Engineers, Walla Walla, WA.

Oldale, R.N. and R.A. Barlow. 1986. Geologic map of Cape Cod and the Islands, Massachusetts. U. S. Geological Survey Map I-1763, Reston, Virginia.

Pohland, F.G. and S.R. Harper. 1985. Critical Review and Summary of Leachate and Gas Production from Landfills, EPA/600/2-86/073, US Environmental Protection Agency, Cincinnati, OH.

Pratt, S.D. and A. Gaines, An Environmental Status Report on Edgartown Great Pond: Bottom Habits and their Flora and Fauna, 1997.

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

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

Sanders, H.L. 1960. Benthic studies in Buzzards Bay III. The structure of the soft-bottom community. Limnology and Oceanography 5:138-153.

Sanders, H.L., J.F. Grassle, G.R. Hampson, L.S. Morse, S. Gameprice, and C.C Jones. 1980. Anatomy of an oil spill: Long-term effects from the grounding of the barge Florida off West Falmouth, MA. Journal of Marine Research 38:265-380.

Saunders Associates (1989) Martha’s Vineyard Landfill Monitoring Well Sampling Program: Final Report

Saunders, D.L. and J. Kalff. 2001. Nitrogen retention in wetlands, lakes and rivers. *Hydrobiologica* 443:205-212.

Shepard, F.C. Waquoit Bay National Estuarine Research Reserve. 1996. "Managing Wastewater: Prospects in Massachusetts for a Decentralized Approach".

Shepard, F.C. Waquoit Bay National Estuarine Research Reserve. 1996. "A Massachusetts Guide to Needs Assessment and Evaluation of Decentralized Wastewater Treatment Alternatives".

Skomal, G.B. (1998) Finfish Survey: Edgartown Great Pond. Third Quarterly Report: Massachusetts Division of Marine Fisheries

Smith and Mahoney (1991) Martha’s Vineyard Landfill Groundwater Quality Monitoring Program: Final Report

Smith, K.N. and B.L. Howes, 2006. Attenuation of watershed nitrogen by a small New England salt marsh. Manuscript in review

Taylor, C.D. and B.L. Howes, 1994. Effect of sampling frequency on measurements of seasonal primary production and oxygen status in near-shore coastal ecosystems. Marine Ecology Progress Series 108: 193-203.

Tian, Y.Q., J.J. Wang, J. A. Duff, B.L. Howes and A. Evgenidou. 2009. Spatial patterns of macrobenthic communities in shallow tidal embayments and association with environmental factors. Journal of Environmental Management 44:119-135.

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

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

Walter, D.A. and A. Whealan. 2005. Simulated Water Sources and Effects of Pumping on Surface and Ground Water, Sagamore and Monomoy Flow Lenses, Cape Cod, Massachusetts. USGS Scientific Investigations Report 2004-5181.

Whitman & Howard. 1994. A Numerical Groundwater Flow Model and Zone II Delineation for the Farm Neck Well, Oak Bluffs, Mass. Wellesley, MA.

Whitman & Howard (1994) A Numerical Groundwater Flow Model and Zone II Delineation for the Farm Neck Well, Oak Bluffs, Mass., Wellesley, Ma.

Whitman & Howard (1996) Letter Report on Second Phase of Nitrate Plume Investigation

Wilcox, W.M. 1996. Tisbury Great Pond Watershed Study. Martha's Vineyard Commission.

Wilcox, W.M. (1998) Island Coastal Ponds Water Quality Survey, 1995-1996: Great Ponds Report. MV Shellfish, MV Commission, UMASS Extension

Wilcox, W.M. (1986) Vineyard Farm Survey. Unpublished Survey.

Wood, J.D., J.S. Ramsey, and S. W. Kelley, (1999). "Two-Dimensional Hydrodynamic Modeling of Barnstable Harbor and Great Marsh, Barnstable, MA." Applied Coastal Research and Engineering, Inc. report prepared for the Town of Barnstable. 28 pp.

Woodruff, R.E. and C.E. Saunders. 1989. Tisbury Great Pond Watershed Study. Prepared for the Planning Boards of Towns of Chilmark and West Tisbury, Massachusetts.

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