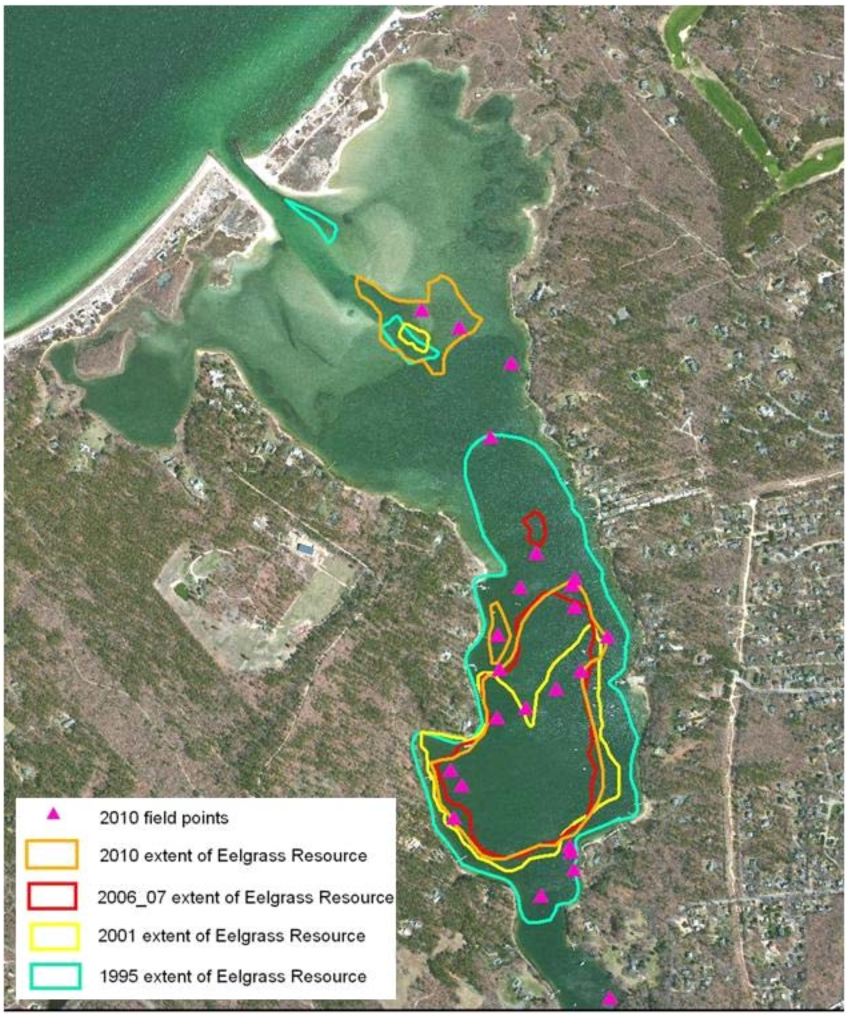
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Lake Tashmoo Estuary Towns of Tisbury, West Tisbury and Oak Bluffs, MA



University of Massachusetts Dartmouth
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Environmental Protection

FINAL REPORT – February 2015

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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 Lake Tashmoo embayment system, a coastal embayment primarily within the Towns of Tisbury, West Tisbury and Oak Bluffs, Massachusetts. It should be noted that a small portion of the mid watershed to Lake Tashmoo exists within the Town of Oak Bluffs. Analyses of the Lake Tashmoo embayment system was performed to assist the Towns of Tisbury, West Tisbury and Oak Bluffs 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 Town's 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 Lake Tashmoo 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 Lake Tashmoo 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 Lake Tashmoo embayment system within the Towns of Tisbury, Oak Bluffs 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 Martha's Vineyard 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 Oak Bluffs and Tisbury are already working collaboratively regarding the future implementation of the MEP nutrient threshold analysis of the Lagoon Pond system. For the Towns of Tisbury, West Tisbury and Oak Bluffs, this analysis of the Lake Tashmoo system will be considered relative to the recently completed nutrient threshold analysis of Lagoon Pond as well as Oak Bluffs Harbor, Farm Pond and Sengekontacket Pond to plan out and implement a unified approach to nutrient management for this part of the island. The MEP report for Lake Tashmoo and the other nearby estuaries are intended to help the Towns work collaboratively as appropriate to maximize the effectiveness of nitrogen management solutions. The Towns of Tisbury, West Tisbury and Oak Bluffs with associated working groups (e.g. Tisbury Waterways) 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 Lake Tashmoo embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Martha's Vineyard Commission and the Town of Tisbury, West Tisbury and Oak Bluffs. 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 each of the Towns that make up the Lake Tashmoo watershed as well as the Martha's Vineyard Commission. The MEP technical team reviewed the sub-regional groundwater model originally prepared by Whitman Howard (1994) and the subsequent update by Earth Tech in order to obtain up to date watershed delineations. This model organized much of the historic USGS geologic data collected on Martha's Vineyard and provided a satisfactory basis for incorporating the MEP refinements necessary to complete the Lake Tashmoo watershed delineation. The watershed boundaries were confirmed by the USGS. These watershed delineations and the land-use data was used to determine watershed nitrogen loads within the Lake Tashmoo 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 Lake Tashmoo embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Vineyard / Nantucket Sound source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Lake Tashmoo 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 Lake Tashmoo embayment system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 and VIII.2 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for the Lake Tashmoo system. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Lake Tashmoo embayment system in the Towns of Tisbury, West Tisbury and Oak Bluffs. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment, however, within this report an additional scenario was undertaken to examine alternative watershed delineations based on future planned effluent disposal sites and how that may affect nitrogen load to Lake Tashmoo. The specifics of this additional management scenario are found in Section IX of the report.

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 80% of the controllable watershed load to the Lake Tashmoo embayment system and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through this source is a good gauge of the feasibility for restoration of these systems.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Lake Tashmoo 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 Lake Tashmoo 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 system is showing some nitrogen related habitat impairment throughout its tidal reaches. The upper basin and lower basin are relatively deep for southeastern Massachusetts estuaries on Vineyard Sound and Buzzards Bay. This structure allows periodic weak salinity stratification (weak vertical mixing), which makes these basins sensitive to the negative effects of nitrogen enrichment. The result is periodic hypoxia in the upper basin and oxygen depletion in the lower basin as a result of in situ phytoplankton production and deposition. It is almost certain that the observed periodic hypoxia in the uppermost headwater basin resulted in the loss of the beds observed in 2001 from the 1995 and 1997 coverage. The pattern of loss is consistent with nitrogen enrichment, following the gradient of increasing nitrogen and chlorophyll-*a* levels from the inlet to the head waters. The decline in eelgrass within these basins makes restoration of eelgrass the target for TMDL development by MassDEP and the primary focus of threshold development for these areas for the MEP. At present the infaunal communities are also moderately impaired in the lower basin, but habitat is significantly impaired to degraded throughout the upper basin as seen by the low numbers of organisms. However, given the level of impairment and the location of this basin within the Lake Tashmoo Estuary, it is certain that restoring eelgrass habitat within the upper and mid-lower basins will result in restoration of the infaunal habitat in the lower portion of the system, as nitrogen enrichment will be significantly reduced throughout the overall estuary.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate conditions of poor habitat quality within the deep basin waters (>3 meters) of Lake Tashmoo under moderately nutrient enriched conditions. It appears that the basins which constitute much of the bottom habitat of Lake Tashmoo are periodically not vertically well mixed during the summer, which allows the moderate level of nutrient enrichment to occasionally produce very low oxygen conditions. The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follows the spatial pattern of total nitrogen levels in this system. It is clear that Lake Tashmoo's nutrient enrichment response is magnified by its basin structure combined with the depositional nature of the basins (as evidenced by the accumulations of drift macroalgae) and periodic reduced vertical mixing. The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate conditions of moderate habitat quality at the Hillman Point mooring location and moderate to poor habitat quality at the Brown Point DO recording site respectively. The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follow the spatial pattern of total nitrogen levels in this system and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuary. However, it is clear that nutrient enrichment response in Lake Tashmoo Pond is magnified by its basin structure, which when combined with the depositional nature of the upper basin (head water to Hillman Point) and accumulations of macroalgae, results in poor quality and benthic animal habitat within the deeper water of the upper basin.

At present, eelgrass beds exist mainly within the mid-upper basin of the Lake Tashmoo Estuary with smaller beds in the lower portion of the system closest to the inlet. In 1951 eelgrass coverage extended throughout the main basin of the estuary from just upgradient of

Kuffies Point to the uppermost tidal reach near the discharge from the freshwater pond at the present herring ladder covering ~114 acres. However, both the 1995 MassDEP and 1997 MVC surveys indicate that eelgrass coverage had been lost in the uppermost reach and certainly from the lower portion of the main basin, primarily the deeper waters, but coverage was still significant at ~90 acres. This trend continued to 2001 with additional loss at the lower and upper margins of the main basin beds further reducing coverage to 38 acres, again with loss mainly from deep waters. The coverage has remained relatively constant to 2010, with losses from the upper basin being more than offset by development of a new bed within the channel to the tidal inlet in the lower portion of the estuary, where water depth is shallow and water quality is maintained at a high level by incoming water from Vineyard Sound.

Overall, the eelgrass observations are diagnostic of a moderate level of nitrogen enrichment, where eelgrass coverage is being reduced over decades in the uppermost tidal basin with elevated average field nitrogen levels of 0.45 mg L^{-1}, levels found in areas that have lost eelgrass in virtually all of the estuaries assessed by the MEP to date. In addition, the eelgrass loss from the deep waters at lower levels of nitrogen enrichment are consistent with observations where lower nitrogen thresholds are required to lower phytoplankton shading of eelgrass beds to allow their persistence at depth within southeastern Massachusetts estuaries. Further, the observation that loss of coverage is relatively recent and that significant eelgrass coverage still exists indicates that this estuary has exceeded nitrogen threshold to support eelgrass, but only by a moderate amount of nitrogen enrichment.

The survey of infauna communities throughout Lake Tashmoo indicated a system presently supporting impaired benthic infaunal habitat throughout its basins, with the upper basin showing significant impairment and the lower basin moderate impairment. The pattern of impairment follows the depth and the hypoxia, macroalgal accumulations and higher phytoplankton biomass in the upper basin and the moderate oxygen depletion, absence of macroalgae and moderate phytoplankton biomass in the lower basin.

The loss of the deep basin infauna habitat results from the observed periodic reduction in vertical mixing by the weak salinity stratification of waters in these deep basins. The effect of the geomorphology of Lake Tashmoo's basins is to increase deposition of organic matter (increasing oxygen uptake from bottom waters) is a system that "isolates" those bottom waters from oxygen rich surface waters for short periods of time (hours to days). The result is periodic hypoxia and anoxia, in part due to nitrogen enrichment and in part due to "natural" processes.

Overall, the infauna survey indicated that deeper areas (>3 meters of the upper basin) are not supportive of infaunal communities and that the entire upper basin south of Hillman Point is currently supporting few infaunal animals. In the upper basin (south) the area with low numbers of organisms covers a large portion of the entire basin. The low numbers likely indicate seasonal re-colonization of the deep basin where summer-time hypoxia occurs. This was similar to adjacent Lagoon Pond system where the deep basins of the entire East Arm averaged < 30 individuals per sample. It should be noted that at these low population levels, Diversity and Evenness are irrelevant, the major finding being the lack of a community.

The lower estuary north of Hillman Point is currently supporting high numbers of individuals but distributed among only a moderate number of species with a low-moderate species diversity. The lower basin is not showing significant nitrogen related habitat impairment as there are few organic enrichment indicators (stress indicators) and species include crustaceans, polychaetes and molluscs, with a prevalence of amphipods in the mid region. These values are indicative of a productive, but moderately impaired habitat

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 Lake Tashmoo system in the Towns of Tisbury, West Tisbury and Oak Bluffs were comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 80% of the controllable watershed nitrogen load to the embayment was from wastewater.

A major finding of the MEP clearly indicates that a single general total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of the Great, Green and Bournes Pond Systems, Popponesset Bay System, the Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay and the analysis of the nearby Lagoon Pond, Sengekontacket Pond system as well as Farm 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 Lake Tashmoo.

The threshold nitrogen levels for the Lake Tashmoo embayment system in Tisbury, West Tisbury and Oak Bluffs were determined as follows:

Lake Tashmoo Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Lake Tashmoo system should reflect both recent pre-degradation habitat quality and be reasonably achievable. Based upon the assessment data (Section VII), the Lake Tashmoo system is presently supportive of habitat in varying states of impairment, depending on the component sub-basins of the overall system (e.g. deep basins in the upper portions of the system near the head compared to shallower areas in the lower portion of the main basin closer to the inlet).

- The primary habitat issue within the Lake Tashmoo Embayment System relates to the general loss of eelgrass beds and impaired infaunal habitat. Using the 1995 coverage data as the baseline, it appears that a minimum eelgrass bed area on the order of 113 acres should be recovered if nitrogen management alternatives are implemented. It is possible that a greater area of eelgrass habitat may be restored, to the extent that there was more eelgrass present in Lake Tashmoo prior to 1995. It does appear that the 91.17 acres is a good approximation, as the 1987 and 1995 surveys generally show the same eelgrass beds. Note that restoration of this eelgrass habitat will necessarily result in restoration of other resources throughout the Lake Tashmoo Embayment System, specifically the shallower eelgrass habitat in the shallow waters along the east and particularly the west shore of the mid and lower basins of the system.

- Analysis of nitrogen levels and eelgrass decline indicate that in the uppermost basin of Lake Tashmoo where eelgrass has been lost, average total nitrogen (TN) from the multi-year Water Quality Monitoring Program was relatively high, 0.45 mg L^{-1}. The present absence of eelgrass from the uppermost basin where it occurred in 1951 and 1995 is consistent with loss of coverage in Lagoon Pond at nitrogen levels of 0.39 mg N L^{-1}. In contrast, eelgrass habitat in Lake Tashmoo appears to be comprised of relatively stable beds in the upper/mid basin area of the system at a TN level of 0.36 mg N L^{-1} (MV4). Eelgrass persists within the deep upper basin at this TN level. At slightly higher nitrogen levels at the uppermost edge of the 1995 eelgrass coverage, where eelgrass has been subsequently lost, tidally averaged TN was slightly higher, 0.386 mg N L^{-1} (water quality model, Chapter VI). So it appears that habitat restoration must lower TN level in the upper basin to less than 0.386 mg N L^{-1}, but not lower than 0.36 mg N L^{-1}.

- From multiple lines of evidence presented in the existing assessment it appears that the threshold for stable eelgrass habitat in Lake Tashmoo must be less than 0.386 mg N L^{-1}, as this is the present level and loss is continuing. Similarly, it appears that eelgrass beds presently extant in adjacent Lagoon Pond at nitrogen levels of 0.371 mg N L^{-1} continue to show some loss. Based upon observations specific to Lake Tashmoo and those from other systems, a tidally averaged nitrogen threshold for Lake Tashmoo of 0.36 mg N L^{-1} will allow restoration of areas of impaired eelgrass habitat. Additionally, this TN level is currently supportive of stable eelgrass habitat within the upper basin of Lake Tashmoo. This threshold is only slightly higher than that for the slightly shallower basins (2-3 m) of West Falmouth Harbor and Phinneys Harbor (0.35 mg N L^{-1}) to account for the increased depth in Lake Tashmoo. In addition, lowering the level of nitrogen enrichment at the sentinel station will lower nitrogen levels throughout the estuary with the parallel effect of improving infaunal habitats throughout the estuary.

For restoration of the Lake Tashmoo Embayment System, the primary nitrogen threshold at the sentinel station (uppermost edge of the 1995 eelgrass coverage in the southern basin and in the channel adjacent Browning Point) will need to be achieved. At the point that the threshold level is attained at the sentinel station, water column nutrient concentrations will also be at a level that will be supportive of healthy infaunal communities. The results of the Linked Watershed-Embayment modeling are used to ascertain that when the nitrogen threshold is attained, TN levels in the regions associated with the secondary criteria of healthy infauna are also within an acceptable range. The goal is to achieve the nitrogen target at the sentinel location and restore healthy eelgrass habitat throughout the lower and upper region of the Lake Tashmoo system (taking into consideration depth and basin structure) as well as infaunal habitat within the shallow sediments throughout the embayment.

It is important to note that the analysis of future nitrogen loading to the Lake Tashmoo 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 Lake Tashmoo estuarine system is that restoration will necessitate a reduction in the present (Oak Bluffs, Edgartown and Tisbury, 2008 and West Tisbury, 2007) 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 Lake Tashmoo estuary system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. (mg/L)
Drew Cove	0.496	1.548	2.885	-	4.433	0.504	7.765	12.702	0.34-0.36	0.360
Tashmoo - main basin	1.460	4.490	15.416	0.294	19.907	3.304	8.750	31.961	0.30-0.31	-
Tashmoo - upper basin	0.096	0.268	0.496	-	0.764	-	-	0.764	0.45	-
Combined Total	**2.052**	**6.307**	**18.797**	**0.294**	**25.104**	**3.808**	**16.515**	**45.427**	**0.30-0.45**	**0.360**

[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 wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings.
[5] atmospheric deposition to embayment surface only
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 2001– 2007 data, ranges show the upper to lower regions (highest-lowest) of an sub-embayment. Individual yearly means and standard deviations in Table VI-1.
[8] Threshold for sentinel site is located at the Wild Harbor water quality station WH-1.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Lake Tashmoo estuarine system in Tisbury, Massachusetts.

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
Drew Cove	4.433	4.144	0.504	6.837	11.486	-6.5%
Tashmoo - main basin	19.907	12.199	3.304	7.792	23.295	-38.7%
Tashmoo - upper basin	0.764	0.764	-	-	0.764	0.0%
Combined Total	**25.104**	**17.107**	**3.808**	**14.630**	**35.546**	**-31.9%**

(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 concentration identified in Table ES-1.
(3) Projected future flux (present rates reduced approximately proportional to watershed load reductions).
(4) Sum of target threshold watershed load, atmospheric deposition load, and benthic flux load.

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I. INTRODUCTION

The Lake Tashmoo Embayment System is a simple estuary located primarily within the Town of Tisbury on the island of Martha's Vineyard, Massachusetts and exchanges tidal water with Vineyard Sound through a single inlet through a barrier beach (Figure I -1). The watershed to the Lake Tashmoo Estuary is distributed mainly amongst the Towns of Tisbury and West Tisbury, with a small portion of the mid watershed area falling within the Town of Oak Bluffs. Land uses and associated nitrogen loads closest to an embayment generally have greater impact than those in the upper portions of the watershed, which are subject to nitrogen attenuation during transport through natural aquatic systems (e.g. ponds, rivers, wetlands etc.) prior to discharge to the embayment. Effective nitrogen management of the Lake Tashmoo System will require consideration of all sources contributing to the nitrogen load reaching the estuarine waters. That the large majority of the Lake Tashmoo watershed lies within the Towns of Tisbury and West Tisbury makes development and implementation of a comprehensive nutrient management and restoration plan for this system less challenging as watershed-wide planning can be simplified by not having to find consensus among many different municipal jurisdictions.

Figure I-1. Location of the Lake Tashmoo Estuary on the north shore of the Island of Martha's Vineyard primarily within the Town of Tisbury, MA. Lake Tashmoo is a drowned valley enclosed by a barrier beach, with a single tidal inlet through which tidal waters are exchanged with Vineyard Sound.

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 (such as nitrogen) that they receive due to the proximity and density of development near and along their shores. The presence of tributary coves (e.g. Rhoda Pond to Lake Tashmoo) to the main basin of the system greatly increases the shoreline and with the "head water stream" (e.g. herring ladder), decreases the travel time of groundwater (and its pollutants) from the watershed recharge areas to estuarine regions of discharge. In particular, the Lake Tashmoo Estuary and its tributary coves, along with many of the other salt pond systems on Martha's Vineyard such as Sengekontacket Pond, Lagoon Pond, Edgartown Great Pond, Tisbury Great Pond, Farm Pond and James Pond, are at risk of eutrophication (over enrichment) from high nitrogen loads entering from groundwater and runoff from the watershed and numerous sub-watersheds.

The primary ecological threat to the Lake Tashmoo Estuary, as a coastal resource, is degradation resulting from nutrient enrichment. Although the watershed and the Pond have some issues relative to bacterial contamination, this does not appear to be having large ecosystem-wide impacts. Bacterial contamination causes closures of shellfish harvest areas, but does not "damage" the habitat for estuarine organisms. In contrast, overloading of the critical eutrophying nutrient (nitrogen) to estuarine waters results in impairment of habitats and frequently loss of fish and shellfish productivity. In the case of the Lake Tashmoo Estuary, nitrogen loading has greatly increased over 1950 levels due to increased seasonal and year-round residents using on-site septic systems for wastewater treatment and disposal and associated increased use of fertilizers and runoff. This increase in nitrogen loading appears to be causing some recent impairment to aquatic resources around Martha's Vineyard. This is discussed in detail in Sections IV and VII.

The Towns of Martha's Vineyard have been among the fastest growing in the Commonwealth over the past two decades and the Towns of Tisbury and Oak Bluffs both do have centralized wastewater treatment systems, however, these facilities are limited in size and reach. The Town of Tisbury operates a 104,000 gallon per day (gpd) wastewater facility but does not receive wastewater from the watershed to Lake Tashmoo, but does have an effluent recharge located at the watershed boundary. Similar to most watersheds in southeastern Massachusetts, the unsewered areas rely on privately maintained septic systems for on-site treatment and disposal of wastewater. As existing and probable increasing levels of nutrients impact the coastal embayments of the Town of Tisbury, water quality degradation will accelerate, with further harm to invaluable environmental resources of the Town and the Island on the whole.

As the primary stakeholder to the Lake Tashmoo Estuary, the Town of Tisbury, in collaboration with the Martha's Vineyard Commission (MVC), has been among the first communities to become concerned over perceived degradation of their coastal embayments. Over the years, this local concern has led to the conduct of numerous studies (see Chapter II) of both water quality and nitrogen loading to the system such as: 1) the Martha's Vineyard Coastal Ponds Water Quality Survey - 2004, 2) Nutrient Loading to Lake Tashmoo, Martha's Vineyard Commission 2003 and 3) Survey of the Eelgrass Beds of Lake Tashmoo - 1997. While critical historical studies have been considered in the MEP analysis of Lake Tashmoo, key in the MEP effort has been the Lake Tashmoo Water Quality Monitoring Program, spearheaded by the MVC and supported by private, municipal, county and state funds (most recently Massachusetts 604(b) grant program) with technical assistance by the Coastal Systems Program at SMAST-UMD. This effort provides the quantitative water column nitrogen data (2001-2007) required for the implementation of the MEP Linked Watershed-Embayment Approach used in the present study.

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

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, members of the Martha's Vineyard Commission and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns of Oak Bluffs, West Tisbury and Tisbury to work collaboratively to develop and evaluate the most cost effective nitrogen management alternatives to restore this valuable coastal resource which is currently being degraded by nitrogen overloading. It is important to note that the Lake Tashmoo Estuary and its associated watershed has been significantly altered by human activities over the past ~100 years. As a result, the present nitrogen “overloading” appears to result partly from alterations to its ecological systems. These alterations subsequently affect nitrogen loading within the watershed and influence the degree to which nitrogen loads impact the estuary. Therefore, restoration of this system should focus on managing nitrogen through both management of nitrogen loading within the watershed and restoration/management of processes which serve to lessen the amount or impact of nitrogen entering the estuary.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

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

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

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

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

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

The major MEP nitrogen management goals are to:

- provide technical analysis and supporting documentation to Towns as a basis for sound nutrient management decision making towards embayment restoration
- develop nutrient management working group(s) for coordination and rapid transfer of results,
- determine the nutrient sensitivity of 70 of the 89 embayments in southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative analysis for TMDL development by MassDEP and USPA, and to support 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 55 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 Management Modeling Approach when properly parameterized, calibrated and verified for a given embayment becomes a nitrogen management planning tool, which fully supports TMDL analysis. The Linked Model Approach 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 Linked 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) estuarine 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-2). This methodology integrates a variety of field data and models, specifically:

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

I.2 SITE DESCRIPTION

Lake Tashmoo is a simple estuary, with a single armored inlet through the barrier beach. The Lake Tashmoo Estuary is a long narrow north/south oriented system that has one small tributary cove referred to as Rhoda Pond, with the main tidal reach consisting of a lower (North basin) and an upper basin (South basin). Tidal water from Vineyard Sound enters the system into the lower (north) basin and travels through a main channel and sand flats before entering a deeper portion (~2-3 m) of the lower basin. Entering water also travels west into the shallow tributary sub-embayment of Rhoda Pond. Water from the lower deep basin is connected to the upper basin via a narrow, relatively deep channel (2-3 m) which extends nearly to the estuary's headwaters (Figure I-3). The Lake Tashmoo Estuary and most of its watershed is situated within the Nantucket Moraine sediments consisting mainly of folded pre-Wisconsin clay, sand, gravel and glacial till overlain by Wisconsin drift (Woodworth and Wigglesworth 1934). Only a relatively small portion of the upper watershed is situated in the sandy outwash plain to the south. These sediments were deposited as the ice sheets retreated at the end of the last glacial period.

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

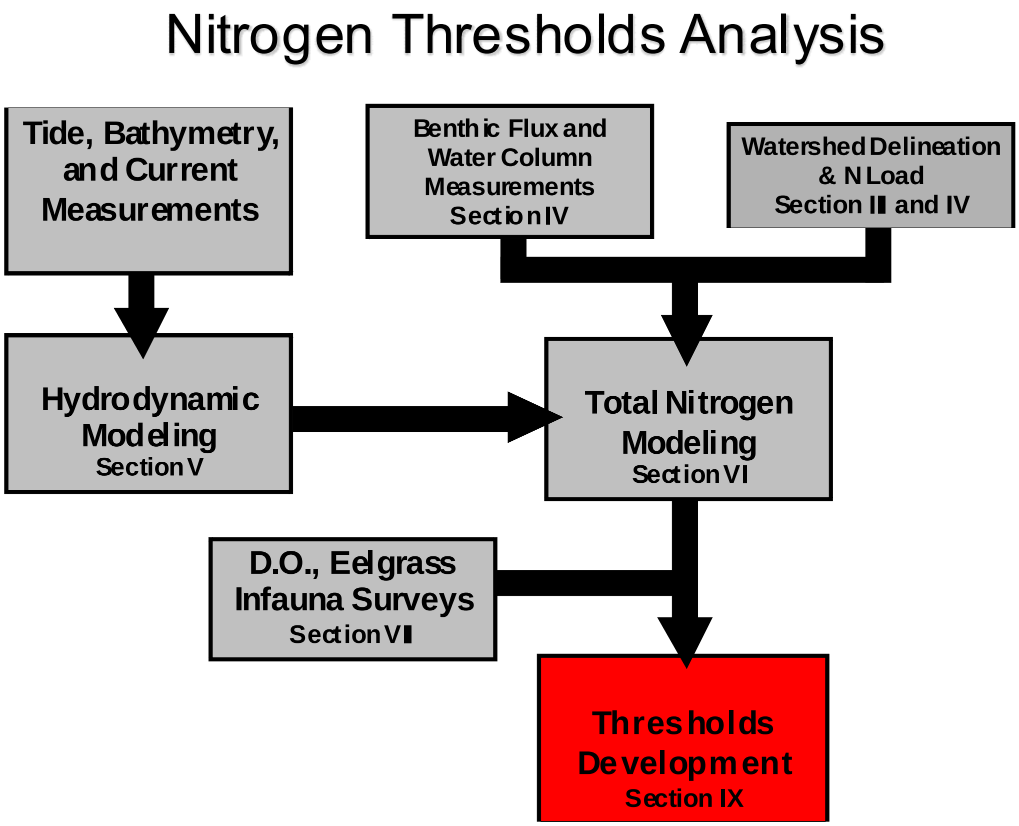

Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

The enclosed Lake Tashmoo Estuary appears to have been formed as a composite estuary, where it appears that a valley possibly partially formed from kettles and stream channels was drowned by rising sea level, with subsequent formation of a lagoon at the northern end created by the formation of a barrier beach via spit growth primarily from the western shore. While formation of the upper tidal reach is less certain, the lagoon is not. Lagoonal estuaries form parallel to coasts and are a major type of estuary along the east coast of the United States. The finding that beach deposits constitute the Vineyard Sound shoreline of Lake Tashmoo favors its formation as a "lagoon". For the MEP analysis, the Lake Tashmoo Estuary was considered as having two main components, a lower portion with the associated Rhoda Pond sub-embayment and an upper portion (southern basin) that receives freshwater flow via a herring run that is connected to a very small freshwater pond (see Figure I-3) which includes a freshwater spring named in the 1800s by the Wampanoag Indians, Kuttashimmoo (the Great Spring).

The formation of the Lake Tashmoo Estuary has and continues to be greatly affected by coastal processes, specifically the role that the barrier beach plays in separating the pond from Vineyard Sound source waters. Prior to the inlet being armored, the ecological and biogeochemical structure of the pond is likely to have changed over time as the barrier beach intermittently closed due to sand transport and deposition by coastal processes and naturally breached in different locations as a function of storm frequency and intensity. It is almost certain that the “open” nature of the existing main basin is geologically an artificial phenomenon, and that the pond would naturally exist mainly as a closed system with occasional inlets opening up from storm activity.

Figure I-3. Estuarine basins for the Massachusetts Estuaries Project analysis of the Lake Tashmoo Estuary. Tidal exchange with Vineyard Sound waters is through the single inlet through the barrier beach. Freshwaters enter from the watershed primarily through direct groundwater discharge with a small outflow from a freshwater pond which is connected to the embayment by a herring run.

I.3 NUTRIENT LOADING

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

Nutrient related water quality decline represents one of the most serious threats to the ecological health of the nearshore coastal waters of Massachusetts (inclusive of Martha's Vineyard and Nantucket) and the United States as a whole. 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) or measured attenuation of nitrogen loads from the watershed to the estuarine receiving water via streams and rivers. 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 (hydrodynamic + water quality) models and site-specific data. In the present effort we have integrated site-specific data on nitrogen inputs, tidal exchange and nitrogen concentrations throughout the associated with the Lake Tashmoo Estuary and monitored by the Martha's Vineyard Commission and the Town of Tisbury. The Water Quality Monitoring Program results with the MEP site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) was utilized to add site specificity to the 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 Lake Tashmoo are near or beyond their ability to assimilate additional nutrients without impacting their ecological health. This is clearly observed in the southern most basin of the system which is furthest away from the clean waters entering the system from Vineyard Sound. Nitrogen levels are elevated throughout the estuary and eelgrass beds have declined measurably over the past 20 years in a manner diagnostic of nitrogen enrichment (i.e. loss of beds in the headwaters and losses in the deeper waters expanding to shallower waters. In addition, infaunal animal habitat has been lost in some basins due to organic matter enrichment and periodic oxygen depletion resulting from nitrogen enrichment. Nitrogen related habitat impairment within the Lake Tashmoo Estuary shows a gradient moving from the inland reaches toward the inlet and the deeper waters (2-3 m) throughout the estuary. The result is that nitrogen management of the primary basins of Lake Tashmoo is aimed at restoration, not protection or maintenance of existing conditions. Fortunately for the citizens of Tisbury, West Tisbury and Oak Bluffs, Lake Tashmoo appears to have reached its nitrogen loading threshold relatively recently, suggesting that only moderate levels of nitrogen management may be required for restoration.

In general, nutrient over-fertilization is termed “eutrophication” and in certain instances can occur naturally over long periods of time. When the nutrient loading is rapid and primarily from human activities leading to changes in a coastal watershed, nutrient enrichment of coastal waters is termed “cultural eutrophication”. Although the influence of human-induced changes has increased nitrogen loading to the Commonwealth's coastal waters and contributed to the degradation in ecological health in many cases, the Lake Tashmoo Estuary generally receives high quality (low nitrogen) tidal waters from Vineyard Sound and only a modest watershed nitrogen load. Lake Tashmoo, unlike many estuaries on Cape Cod currently supports significant, although diminishing, eelgrass habitat. The quantitative role of the stable and armored tidal inlet at the northern end of the pond was also considered in the MEP nutrient threshold analysis. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a “pristine” system due to structural characteristics, however, these specifics are incorporated into the MEP nutrient threshold analysis.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” (e.g. watershed derived and offshore nutrient inputs) for water quality modeling of the Lake Tashmoo Estuary; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within a given 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 Lake Tashmoo Estuary, including the tributary sub-embayment of Rhoda Pond. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents at the one inlet to the embayment system and water elevations was employed for the hydrodynamic analysis of the entire Lake Tashmoo system. Once the hydrodynamic properties of each component of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for an estuarine system of this type, the water quality and hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties of the system. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon MEP refined (working with the USGS and the MVC) watershed delineations originally developed by Earth Tech. Almost all nitrogen entering the Lake Tashmoo System is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Vineyard Sound source waters and throughout the Lake Tashmoo system were taken from the Town of Tisbury/MVC Water Quality Monitoring Program (a coordinated effort between the Towns of Tisbury, the Martha's Vineyard Commission and the Coastal Systems Program at SMAST). Measurements of current salinity and nitrogen as well as salinity distributions throughout estuarine waters of the System (2001-2007) were used to calibrate the water quality model (under existing loading conditions) and to verify the model results.

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment management modeling approach as applied to the Lake Tashmoo Estuary for the Town of 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 (Section IV) and offshore water column nitrogen values were derived from an analysis of monitoring stations in the adjacent Sound waters as described in Section 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 estuary 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 estuary. This latter assessment represents only one of many solutions and is produced to assist the Town(s) in developing a variety of alternative nitrogen management options for this system and the results of the nitrogen modeling for the selected scenario is also 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 large deep burrowing forms (which include economically important species), to low diversity small shallow dwelling organisms. This shift alone causes significant degradation of the resource and a loss of productivity to both the local shell fisherman and to the sport-fishery and offshore fin fishery. Both the sport-fishery and the offshore fin fishery are dependent upon highly productive estuarine systems as habitat and for food resources 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 generally a natural phase in the evolution of an estuary.

In most marine and estuarine systems, such as Lake Tashmoo, 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 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).

Many of these tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. In contrast, some approaches can be tailored for each individual estuary of interest, but require large amounts of site-specific information and therefore are not generally applied. The present Massachusetts Estuaries Project (MEP) effort uses one such site-specific approach. The assessment focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species within individual estuaries. The linked watershed-embayment management modeling approach is built using embayment specific measurements, thus enabling calibration of the prediction process for the specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Lake Tashmoo Estuary. As the MEP approach requires substantial amounts of site-specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of “data mining” and to gather additional information on an estuary’s habitat quality and unique features.

A number of studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Lake Tashmoo Estuary and associated watershed over the past three decades.

Nutrient Loading to Lake Tashmoo, Martha's Vineyard Commission (2003) - As a result of growing concerns over the health of the coastal ponds of Martha's Vineyard, the MVC undertook a water quality study of Lake Tashmoo with support from Massachusetts Executive Office of Environmental Affairs and the Massachusetts Department of Environmental Protection. As summarized in the 2003 report, Lake Tashmoo supports important shellfish resources and diverse fish populations, including herring, which are an important food source for both commercial offshore fish species and near shore recreational fish species such as bluefish and striped bass. Also, years of shellfish closures prompted concern over potential impacts from increased human activity in the watershed. Prior to the MVC report, there had been very little research or data-gathering completed that related to Lake Tashmoo and very little was known about its water quality. In response to shellfish closures and growing awareness of issues of habitat impairment resulting from nutrient over-enrichment, an initial four rounds of water sampling were made in Lake Tashmoo between July and September, 2001 at six stations: Head of Pond (1), Drew Cove (2), Rhoda Pond (3), Inlet (4), near Flat Point (5) and at the Town Landing (6). As with all water quality sampling undertaken in support of the MEP and coordinated by the SMAST Coastal Systems Program, all sampling rounds completed by the MVC were made in the early morning hours in order to adequately record dissolved oxygen levels, and on an ebb tide in order to sample the outgoing water rather than the incoming seawater. The water quality sampling program included chemical composition parameters. The aim of the water quality monitoring was to assist in identifying nutrient loading problems that may exist in Lake Tashmoo during present (2001) loading conditions, thereby providing a "snapshot" of existing nutrient loading conditions as well as possibly pointing out localized nutrient related water quality impairments in various parts of the pond.

The 2001 sampling was considered as 4 snapshots of nutrient related water quality conditions. Sampling was spatially distributed throughout the Lake Tashmoo Estuary, distributed throughout the summer months representing worst-case conditions over the year. The results obtained from the summer of 2001 were compared to groundwater sampling undertaken in 1999. In 1999, students from Martha's Vineyard Regional High School sampled groundwater adjacent to the shore of the pond and found total nitrogen concentrations averaging 0.93 mg/l, with slightly higher values on the eastern versus western shore, reflecting the greater density of development in that part of the watershed. According to the MVC, the findings were consistent with the MVC nutrient concentration data. Interestingly, the estuarine nitrogen levels were lower in Lake Tashmoo than for many other Martha's Vineyard estuaries, consistent with the relatively low groundwater TN levels and the consistent tidal flushing in 2001.

In 1997, a survey of eelgrass was also completed by the MVC which provided insight into the water quality results. As summarized in the 2003 report, from the survey, eelgrass was found to be generally abundant and healthy. The low nutrient levels and high water clarity found in the 2001 data was consistent with the eelgrass survey results. The water column was clear to the bottom at stations 2-6 at all times, with extinctions ranging from 1.8 to 2.8 meters in the upper tidal reach. According to the MVC, the eelgrass survey suggested that beds were reduced in areas heavily impacted by boating. The MVC noted a large gap in eelgrass coverage, coincident with the large mooring field in the vicinity of the town landing and possibly the result of periodic increases in turbidity and direct disturbances associated with boating.

Martha's Vineyard Coastal Pond Water Quality Survey Summer 2004, Martha's Vineyard Commission (2006) – This project was completed by the Martha's Vineyard Commission as made possible by a grant from the Massachusetts Department of Environmental Protection (DEP) under the 604(b) program. The University of Massachusetts School of Marine Science and Technology (SMAST) provided sample analyses at no charge. Sampling was completed

by a wide range of trained volunteers including staff from the SMAST Coastal Systems Program.
The primary goal of the MVC project was to continue to build a water quality database for seven of Martha's Vineyard's estuaries and to further prepare them for entry into the Commonwealth's Massachusetts Estuaries Project. The Ponds included in the 2004 survey were: Chilmark Pond, Sengekontacket Pond, Farm Pond, Tashmoo Pond, Cape Poge Pond, Pocha Pond and Lagoon Pond.

According to the MVC report, nitrogen levels deemed acceptable during 2003 were generally similar to those in 2004. There was an increasing gradient in TON from offshore and in the region of the tidal inlet moving toward the estuarine headwaters. Chlorophyll pigment concentrations followed a similar pattern, increasing moving up-gradient into the pond and were also deemed "acceptable" during the study period on average. Dissolved oxygen saturation in the deeper water was also at acceptable levels during the study period but declined in August and indicated the need for some continuous records to capture the overnight D.O. minimum. In 2004, the patterns in water quality metrics were similar to 2004 surveys, however, TN concentrations exceeded the poor water quality limit (according to the MVC) in the mid-pond reach with Chlorophyll concentrations in the southern lower basin exceeding the MVC poor water quality limit (Note: most likely referring to the Buzzards Bay Eutrophication Index rating scheme for the definition of what constitutes "poor" water quality). Dissolved inorganic nitrogen concentrations were low throughout the Lake Tashmoo with the outlet from the spring located at the head of the system being an apparent source of nitrogen with concentrations averaging ~0.17 mg L^{-1}.

MVC/Town of Tisbury/SMAST Water Quality Monitoring Program (2002-2007) - The Martha's Vineyard Commission partnered with SMAST-Coastal Systems Program scientists in 2002 to develop and implement a nutrient related water quality monitoring program for the estuaries of Martha's Vineyard, inclusive of Lake Tashmoo within the Town of Tisbury. The Martha's Vineyard Commission working with the Town of Tisbury Shellfish Department and SMAST Coastal Systems Program scientists coordinated and executed the water quality surveys of the Lake Tashmoo System. For Lake Tashmoo as well as the other estuarine systems of Martha's Vineyard, the focus of the effort has been to gather quantitative site-specific data on the nitrogen related water quality throughout the estuarine reach of the system to support assessments of habitat health and to link watershed and hydrodynamic analysis. These baseline water quality data are a prerequisite to entry into the MEP and the conduct of its Linked Watershed-Embayment Management Modeling Approach. The water quality monitoring program was initiated in 2002 with support from the Massachusetts 604B Grant Program and continued each summer through 2007. Throughout the water quality monitoring period, sampling was undertaken between 4 and 5 times per summer during the warmest months (e.g. June through September), the critical period for nitrogen related water quality decline in southeastern Massachusetts estuaries. The MVC/Town based Water Quality Monitoring Program assayed baseline nutrient related water quality data for 7 sampling stations distributed throughout the main basin of the Lake Tashmoo Estuary, as well as sampling water flowing out of the spring situated in the uppermost portion of the system (Figure II-1a and b). As restoration plans for this and other various systems on Martha's Vineyard are implemented by the Towns, monitoring will have to be resumed or continued to provide quantitative information to the Towns relative to the efficacy of remediation efforts and to allow " tuning via "adaptive management".

Regulatory Assessments of Lake Tashmoo Resources - The Lake Tashmoo Estuary contains a variety of natural resources of value to the citizens of Tisbury as well as to enhancing the productivity of the coastal waters of the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these aquatic resources. The MEP gathers the available information on these resources as part of its assessment, and presents them here (Figures II-2 through II-4) for reference by those providing stewardship for this estuary. For the Lake Tashmoo Estuary these include:

- Mouth of River designation – MassDEP (not applicable for Lake Tashmoo system)
- Designated Shellfish Growing Area – MassDMF (Figure II-2)
- Shellfish Suitability Areas - MassDMF (Figure II-3)
- Anadromous Fish Runs - MassDMF (not applicable for Lake Tashmoo system)
- Priority and Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-4)

It should be noted that the DMF specifies that the areas depicted in Figure II-3 are shellfish suitability areas (areas that have the potential to support a species), not areas that currently support these shellfish resources. While the MEP cannot confirm the presence of bay scallops or soft shell clams in all areas as depicted in the figure, the MEP field surveys did find bay scallops, quahogs and soft shell clams in some areas. However, the MEP data collection was not at the level necessary to confirm the distribution of shellfish species.

Implementation of the MEP's Linked Watershed-Embayment Approach incorporates the quantitative water column nitrogen data (2002-2007) gathered by the Water Quality Monitoring Program and watershed and embayment data collected by MEP staff. The MEP effort also builds upon previous watershed delineation and land-use analyses, the previous embayment hydrodynamic modeling (by MEP staff) and historical eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Lake Tashmoo Estuarine System. The MEP has incorporated all appropriate data from previous studies to enhance the development of nitrogen thresholds for the Lake Tashmoo System and to reduce costs of restoration for the Town of Tisbury.

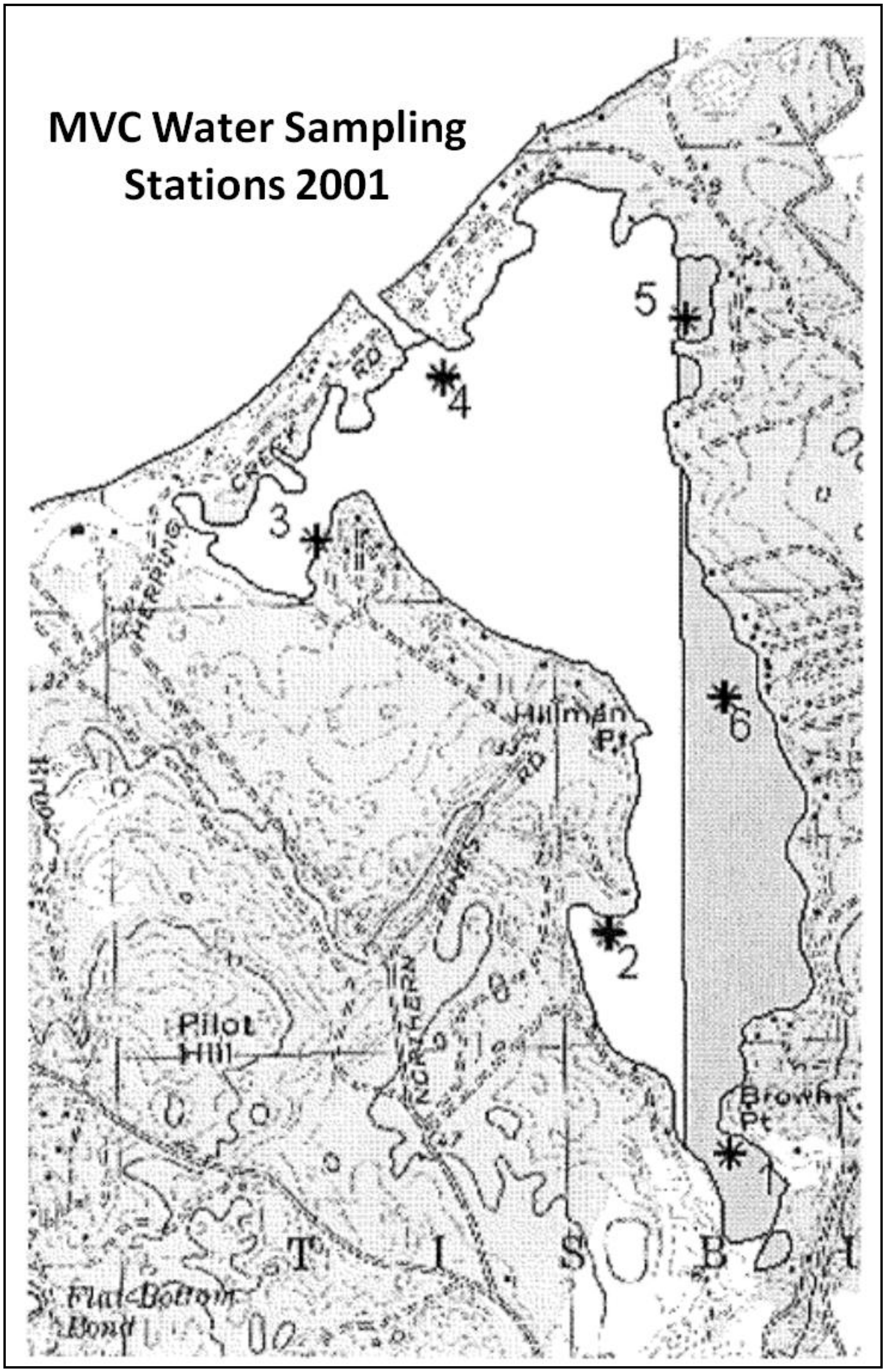

Figure II-1a. MVC/Town of Tisbury initial Water Quality Monitoring Program (2001). Estuarine water quality monitoring stations (1-6) sampled by the MVC/volunteers.

Figure II-1b. MVC/Town of Tisbury Water Quality Monitoring Program. The six (6) estuarine water quality monitoring stations sampled by the MVC/SMAST/Town and volunteers were in different locations that in 2001. Stream water quality station depicted in Section IV and sampled weekly by the MEP.

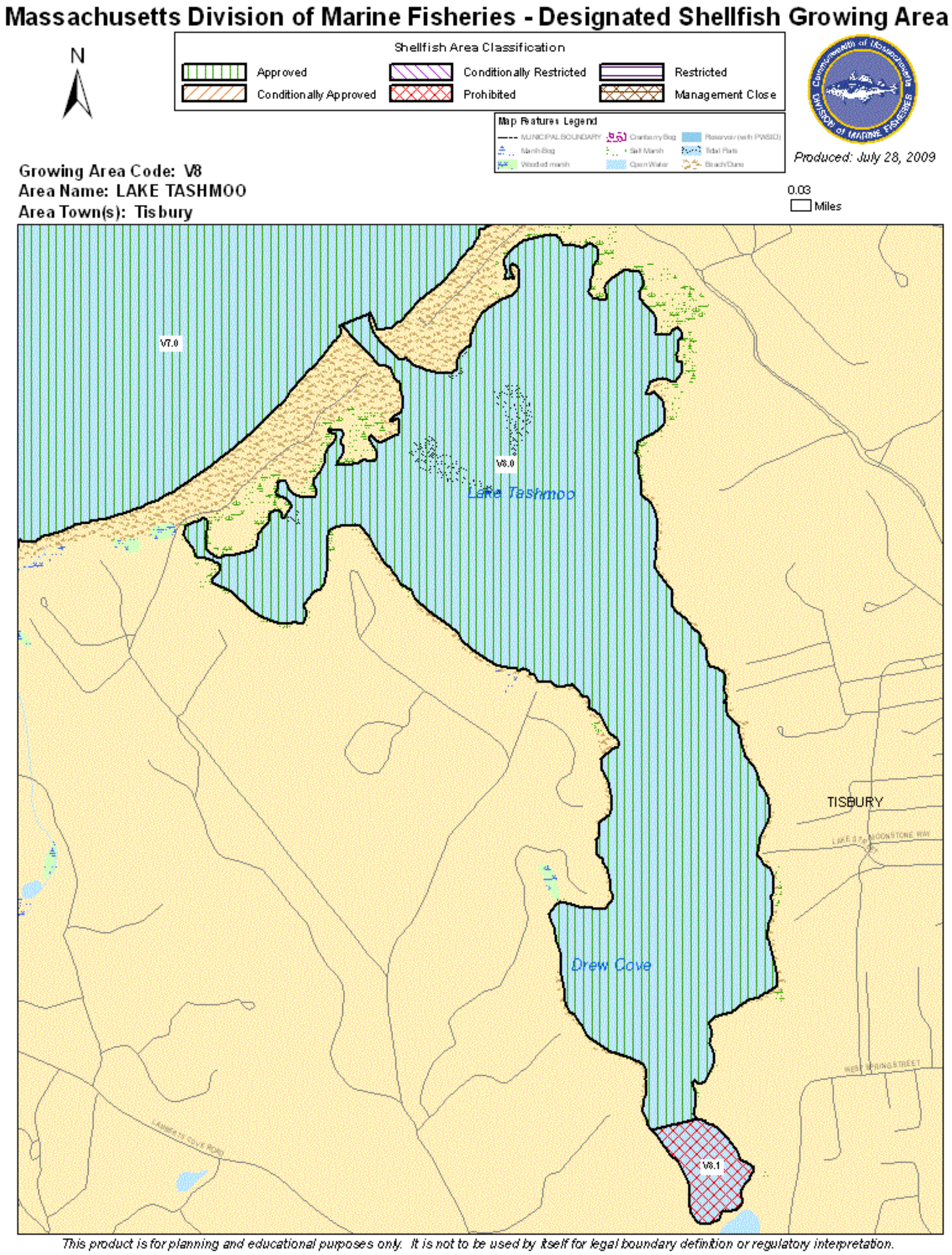

Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

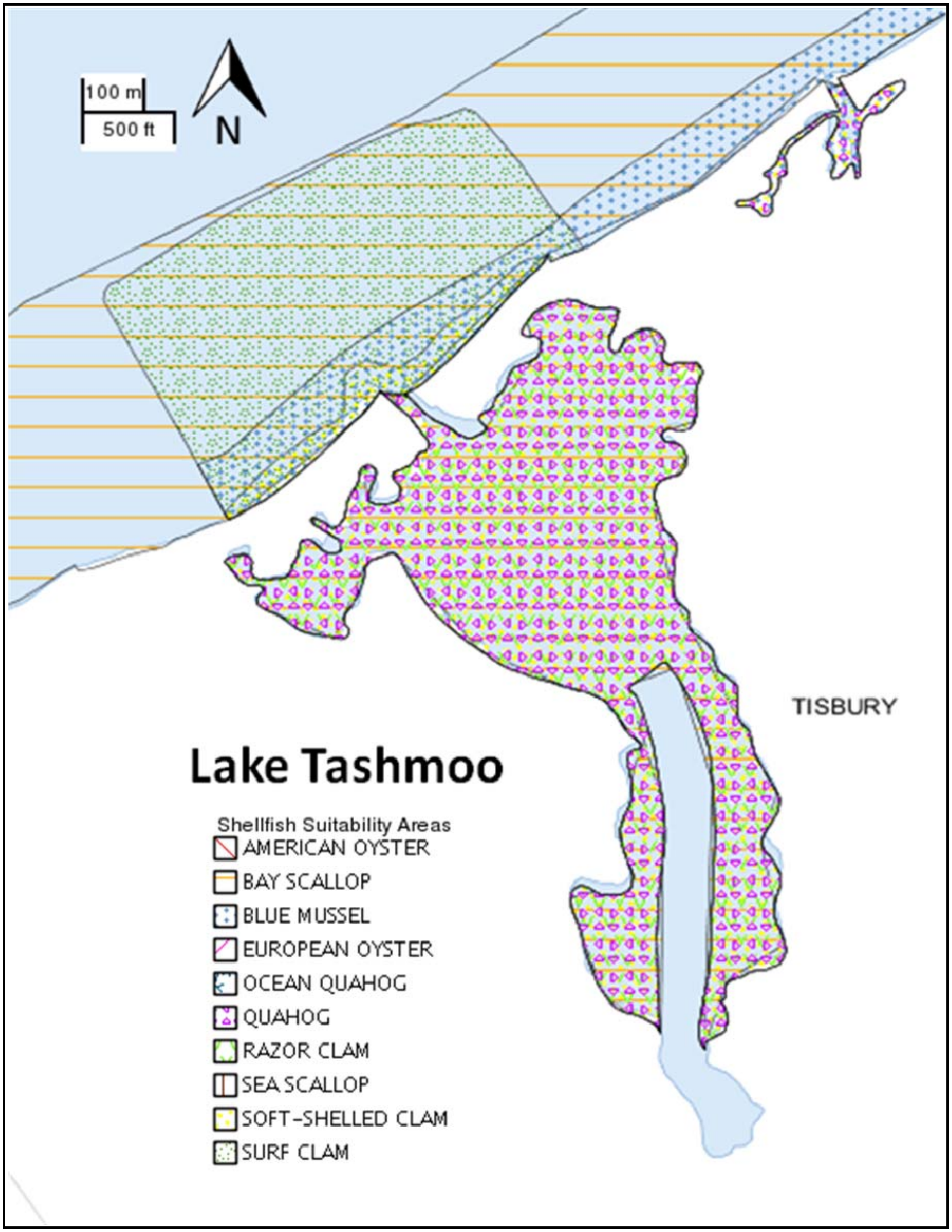

Figure II-3. Location of shellfish suitability areas within the Lake Tashmoo Estuary as determined by Mass Division of Marine Fisheries. Suitability indicates that a species of shellfish will likely be able to grow and does not necessarily mean "presence".

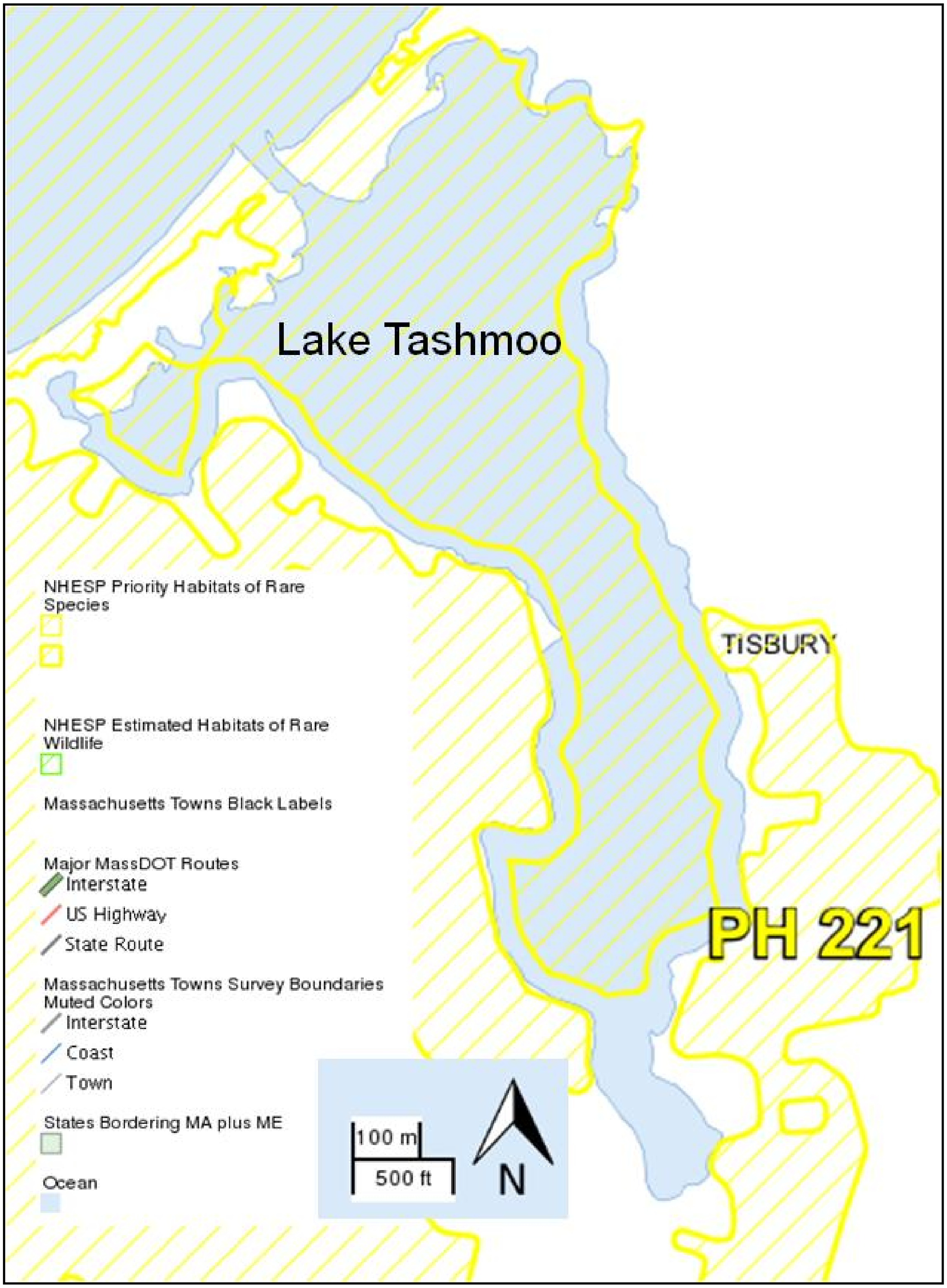

Figure II-4. Priority and Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Lake Tashmoo Estuary as determined by the Massachusetts Natural Heritage and Endangered Species Program (NHESP).

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

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

The relatively porous deposits that comprise most of the Vineyard outwash plain create a hydrologic environment where watersheds are usually better defined by elevation of the groundwater table and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). Delaney (1980) and other subsequent characterizations have indicated that these characteristics also apply to the eastern moraine. Groundwater modeling on Martha's Vineyard has largely been confined to these more porous and relatively simple geologic settings.

Characterizations of the western moraine are very limited and are likely to be very site-specific given its complex geologic mix. Regional groundwater contours created for the United States Geological Survey (USGS) regional water table map do not extend into the western moraine and there were only a few wells drilled within the moraine (Delaney, 1980). The study grid for the regional MODFLOW groundwater model of the island originally developed by Whitman and Howard (1994) and updated by EarthTech, Inc. is tilted to avoid the western moraine and includes a no-flow boundary at the western/moraine edge of the model grid. More recent updates of surficial geology show the western moraine as a mixture of thrust-fault moraine deposits and glacial moraine deposits (Stone and DiGiacomo-Cohen, 2009).

The Lake Tashmoo watershed contains portions of both the eastern and central outwash plain, while the western edge generally follows the eastern edge of the western moraine boundary. The portions of the Lake Tashmoo watershed within the outwash plain and eastern moraine are generally consistent with USGS regional groundwater contours (Delaney, 1980). A 1991 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 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 Earth Tech, Inc. This existing model was used, together with the MODPATH USGS particle tracker, to delineate the groundwater watersheds throughout Martha's Vineyard, including Lake Tashmoo. 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 MVC staff to jointly re-review and refine the delineations in both the outwash and moraine portions of the Lake Tashmoo watershed and subwatersheds. Generally these reviews found that the Martha's Vineyard Commission watersheds are an adequate basis for MEP watershed land-use analysis.

The Lake Tashmoo Estuary and the eastern edge of its watershed are located within the eastern moraine and the eastern watershed boundary is a watershed divide between Lake Tashmoo and Vineyard Haven Harbor. As the watershed line moves toward the south, it eventually forms a divide with the Lagoon Pond watershed boundary (Howes, *et al.*, 2010). The western boundary generally follows the generalized surficial western moraine boundary, as it has been conceptualized in regional groundwater models (*e.g.*, Schwalbaum, 1994). This boundary is reasonable based on an updated synthesis of available geologic/soils data (Stone and DiGiacomo-Cohen, 2009).

The Town of Tisbury is currently conducting an Effluent Disposal Project that is looking at the potential impact of wastewater effluent disposal at three potential sites: 1) Town Hall Annex, 2) Elementary School site, and 3) Public Works site. As part of the project, the town's wastewater consultants used a portion of the regional Earth Tech groundwater model and refined this telescoped portion with new subsurface, well information gathered in 2012 and 2013 (Wright-Pierce, 2013). The model domain for the groundwater modeling for this project included the peninsula between the Lake Tashmoo Estuary and Vineyard Haven Harbor and extended to just south of the former town landfill (near Upland Drive). The groundwater modeling effort included particle tracking to determine contributing areas to estuarine waters and watershed divides. Review of the modeling by MEP staff found that the portion of the watershed to the Lake Tashmoo Estuary that exists within the model domain generally agreed with previous MVC delineations except near the southern boundary of the model domain between Lake Tashmoo and Lagoon Pond.

After reviewing the potential causes of these differences, MEP staff decided to continue to rely on the MVC Lake Tashmoo watershed delineation. MEP staff have a number of technical questions about the Effluent Disposal Project groundwater modeling, which were submitted to the town's wastewater consultants, but generally found that the MVC watersheds were preferred for a number of reasons, including: a) the Wright-Pierce model domain only included ~20% of the Lake Tashmoo Estuary watershed and did not include the rest of the watershed, b) the MVC watershed delineations are comprehensive and island-wide, a similar basis is not provided by the limited area of the Wright-Pierce modeling, and c) the differences in the Lake Tashmoo Estuary watershed delineation do not meaningfully impact the assessment of the potential Tisbury effluent disposal sites.

III.2 LAKE TASHMOO CONTRIBUTORY AREAS

The overall MEP Lake Tashmoo Estuary watershed is situated in the northern portion of Martha's Vineyard, is bounded by Vineyard Sound to the north and is contained within the Towns of Tisbury, West Tisbury and Oak Bluffs (Figure III-1). The Lake Tashmoo Estuary watershed and subwatershed delineations are based on: 1) water table contours modeled throughout the main island outwash plain and eastern moraine and 2) the location of the regional 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 generally follows the eastern border of the western regional moraine, as do all other available delineations.

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 Lake Tashmoo and its sub-estuaries within the model domain. This effort was coordinated among MVC, USGS, and other MEP team members.

Table III-1 provides the daily freshwater discharge volumes for the sub-watersheds associated with the Lake Tashmoo Estuary, as calculated from the recharge areas. These discharge volumes were used in the salinity calibration of the MEP water quality model and to determine hydrologic turnover in any freshwater bodies (e.g. lakes/ponds), as well as for comparison to the directly measured surface water discharges. The overall estimated freshwater flow into the Lake Tashmoo Estuary from the MEP delineated watershed is 21,483 m3/d. The overall MEP watershed area to the Lake Tashmoo Embayment System is 2,658 acres (Table III-1).

The estimated watershed flow (sub-watershed 3) was 16% higher than measured flow at the MEP gauge on the outflow from Upper Tashmoo, a fresh pond/spring with continuous stream flow measurements during the 2004 water year (September 2003 to August 2004, see Section IV.2). The measured flows are used for calibration of the estuarine water quality model, but staff compared groundwater levels and precipitation rates during the gauging period to evaluate whether the slightly higher estimated flows were reasonable. Groundwater elevations at the nearest long-term USGS water level monitoring well (TOW-18 in Tisbury) were within 1% of the long-term average. Groundwater elevations have generally been collected at this monitoring well monthly between 1991 and 2014 (May 14, 2014 download from USGS National Water Information System). In contrast, precipitation during the water year was 16% below average at the Martha's Vineyard Airport (May 9, 2014 download from NOAA National Climatic Data Center). This finding suggests that the flow from Upper Lake Tashmoo is more closely determined by precipitation than local groundwater levels. Further evaluation of the pond depth and sediment characteristics may help to clarify whether there are characteristics that limit or hinder connection with the surrounding groundwater system or whether the pond's location just

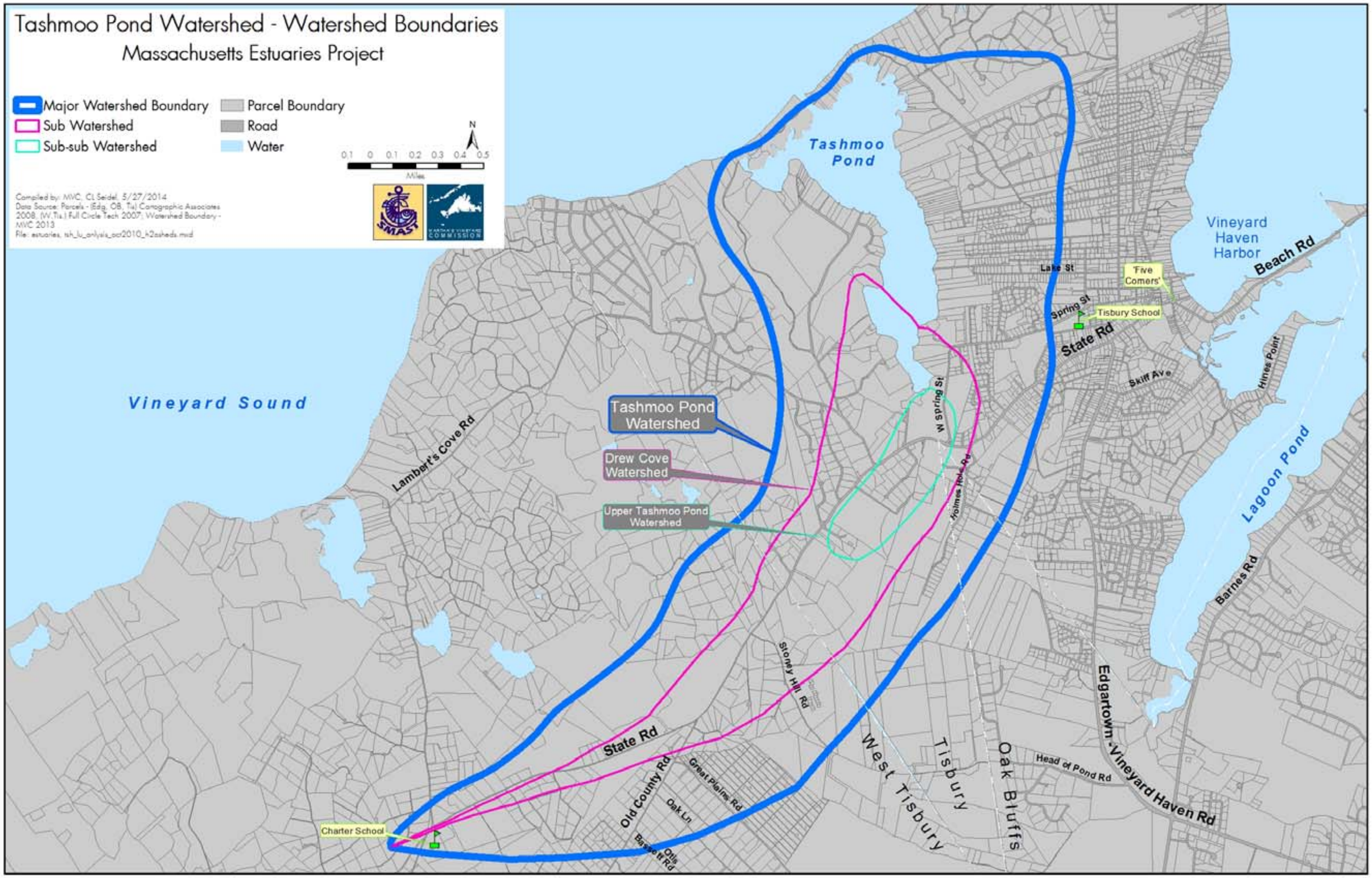

Figure III-1. Watershed and sub-watershed delineations for the Lake Tashmoo Estuary. Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see Section VI).

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

Watershed	Watershed #	Watershed Area (acres)	Groundwater Discharge	
			m^3/day	ft^3/day
Drew Cove	1	625	5,049	178,296
Tashmoo Estuary Main Basin	2	1,905	15,396	543,694
Upper Tashmoo (fresh)	3	129	1,039	36,686
TOTAL		2,658	21,483	758,676

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.

upstream of the location is influencing flow/water levels in the pond. The review of these datasets and their differential variabilities suggests that the estimated watershed flow and measured flow are in reasonable congruence.

The MVC/MEP Lake Tashmoo watershed was used for determining the land area contributing both freshwater and nitrogen inputs to the estuary. In order to develop the freshwater discharge, MEP staff developed daily groundwater discharge volumes based on the various sub-watershed areas and an island-specific recharge rate. The MEP island-specific recharge rate is 28.7 inches/year. This recharge rate estimate is largely based on review of the relationship between recharge and precipitation rates used on Cape Cod. In the preparation of the regional 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. Precipitation data collected since 1947 by the National Weather Service at an Edgartown station has an average precipitation rate over the last 20 years of 46.9 in/yr, very close to the Cape Cod average (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 relationship between recharge and precipitation is reasonable for Martha's Vineyard given the similarity of the geologic material and its origin with that of Cape Cod. This rate has been used for all MEP reports on Martha's Vineyard and was developed in consultation with MVC staff.

The MVC/MEP delineation appears to be the first delineation of the Lake Tashmoo watershed. Previous available reports and MVC decisions all refer to a MVC watershed delineation, but the available reports do not have accompanying maps showing the delineation (*e.g.*, Taylor, 2003). It is unclear whether the MVC has altered the delineation over the years.

Based on the review of the available data and reports, MEP Technical Team staff is confident that the delineation in Figure III-1 is accurate and an appropriate basis for completion of the linked watershed-embayment model for the Lake Tashmoo Estuary. Figure III-1 shows the overall Lake Tashmoo MEP watershed and the three subwatersheds, including sub-watersheds to Upper Lake Tashmoo (fresh) and Drew Cove. The watershed areas and the island-specific recharge rate were used to estimate direct groundwater flow to Lake Tashmoo and each of the subwatersheds (see Table III-1). The subwatershed discharge volumes were used to assist in the salinity calibration of the water quality model.

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

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 Lake Tashmoo 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 Lake Tashmoo Estuary with Martha's Vineyard Commission (MVC) staff. This effort led to the development of nitrogen-loading rates (Section IV.1) to the Lake Tashmoo watershed (Section III). The Lake Tashmoo watershed was sub-divided into three (3) sub-watersheds, including Upper Lake Tashmoo (fresh), to define contributing areas to each of the major sub-watersheds and basins within the Lake Tashmoo Estuary.

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

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. Attenuation through 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 Lake Tashmoo watershed, there are no measured streams or freshwater ponds with delineated watersheds other than the small pond at the head of the estuary. Other, smaller aquatic features within the watershed to Lake Tashmoo do not have separate watersheds delineated and, thus attenuation in these features is not explicitly included in the watershed analysis. If these small features were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (~5%) overestimated given the distribution and size of nitrogen sources and the locations of these features within the watershed.

Based upon the evaluation of the watershed and the various estimated sources of nitrogen, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the sub-watersheds that directly discharge groundwater to the estuary. Internal nitrogen recycling was also determined throughout the tidal reaches of the Lake Tashmoo Estuary; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Martha's Vineyard Commission (MVC) staff, with the guidance of MEP staff, combined Towns of Tisbury, Oak Bluffs, and West Tisbury digital parcel and tax assessors' data from the MVC Geographic Information Systems Department. Digital parcels and land use/assessors data for each of the towns are from 2010. These land use databases contain traditional information regarding land use classifications (*e.g.*, MADOR, 2012) plus additional information developed by the MVC.

Figure IV-1 shows the land uses within the Lake Tashmoo Estuary watershed area. Land uses in the study area are grouped into eight land use categories: 1) residential, 2) commercial, 3) mixed use, 4) agricultural, 5) recreational/golf course, 6) undeveloped (including residential open space), 7) public service/government, including road rights-of-way, and 8) unknown/unclassified. These eight land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2012). Unknown/unclassified are properties that do not have an assigned land use code in the town assessor's database. "Public service" lands are 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.

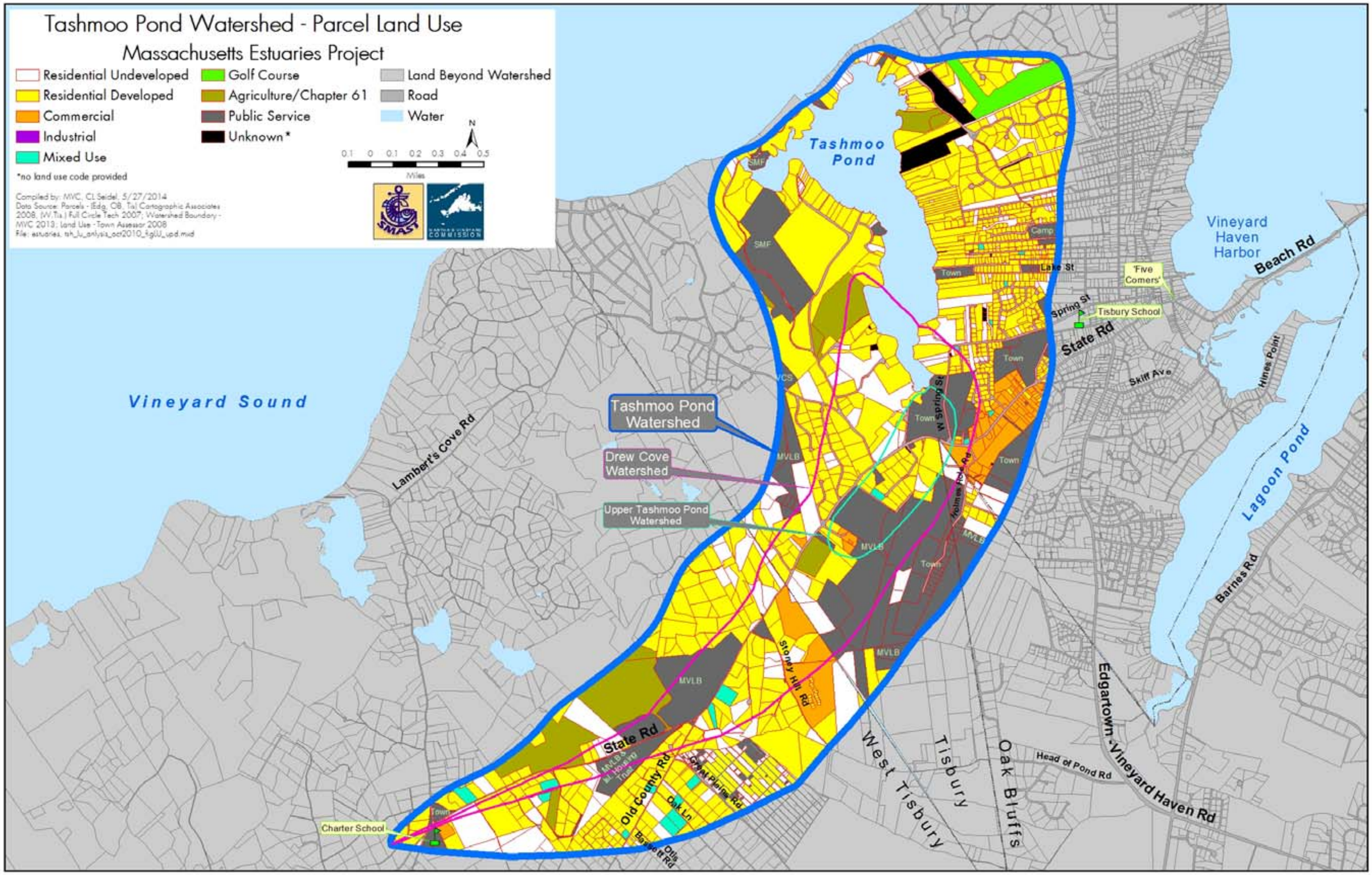

Figure IV-1. Land-use in the Lake Tashmoo watershed. Watershed extends across portions of three towns: Tisbury, West Tisbury, and Oak Bluffs. Land use classifications are based on town assessors' records and general categories in MassDOR (2012).

In the overall Lake Tashmoo System watershed, the predominant land use based on area is residential use, which accounts for 48% of the overall watershed area; public service lands represent the second highest percentage (25%) of watershed area (Figure IV-2). Single-family residences (MADOR land use code 101) are 73% of the overall system residential land area. Residential land uses are also the dominant land use in the Drew Cove and Lake Tashmoo Main sub-watersheds, while public service lands are the dominant land use in the Upper Lake Tashmoo sub-watershed. Undeveloped land is the third-most predominant land use in all three sub-watersheds. Overall, undeveloped lands account for 16% of the entire Lake Tashmoo watershed area.

In a review of parcel counts in the sub-watershed groupings shown in Figure IV-2, residential parcels are the dominant parcel type in all sub-watersheds, generally ranging between 56% and 65% of all parcels in these sub-watersheds. In each of the sub-watersheds, undeveloped parcels are the second most frequent parcel type, ranging between 18% and 21% of the sub-watershed parcel counts. This is a relatively high percentage for undeveloped parcels and suggests that many of these parcels have been previously subdivided rather than being preserved as large contiguous parcels. Overall, 64% of all parcels in the whole Lake Tashmoo watershed are classified as residential. Single-family residences (MassDOR land use code 101) are 76% to 80% of residential parcels in the individual sub-watersheds and 79% of the residential parcels throughout the whole watershed to Lake Tashmoo .

In order to estimate wastewater flows within the Lake Tashmoo study area, MVC staff also obtained parcel-by-parcel water use data from the Towns of Tisbury and Oak Bluffs. Four years of metered water use was obtained for each town, although Oak Bluffs water use is from 2003 to 2006, while Tisbury water use is from 2002 to 2005. The water use data was linked to the town parcel database and assessor's data.

Measured water use is used to estimate wastewater nitrogen loading from individual parcels; average water use is used for each parcel with multiple years of data. The final wastewater nitrogen load for each parcel is based upon the measured water-use, wastewater nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2). All parcels are assumed to use on-site septic systems unless additional information is available.

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}.

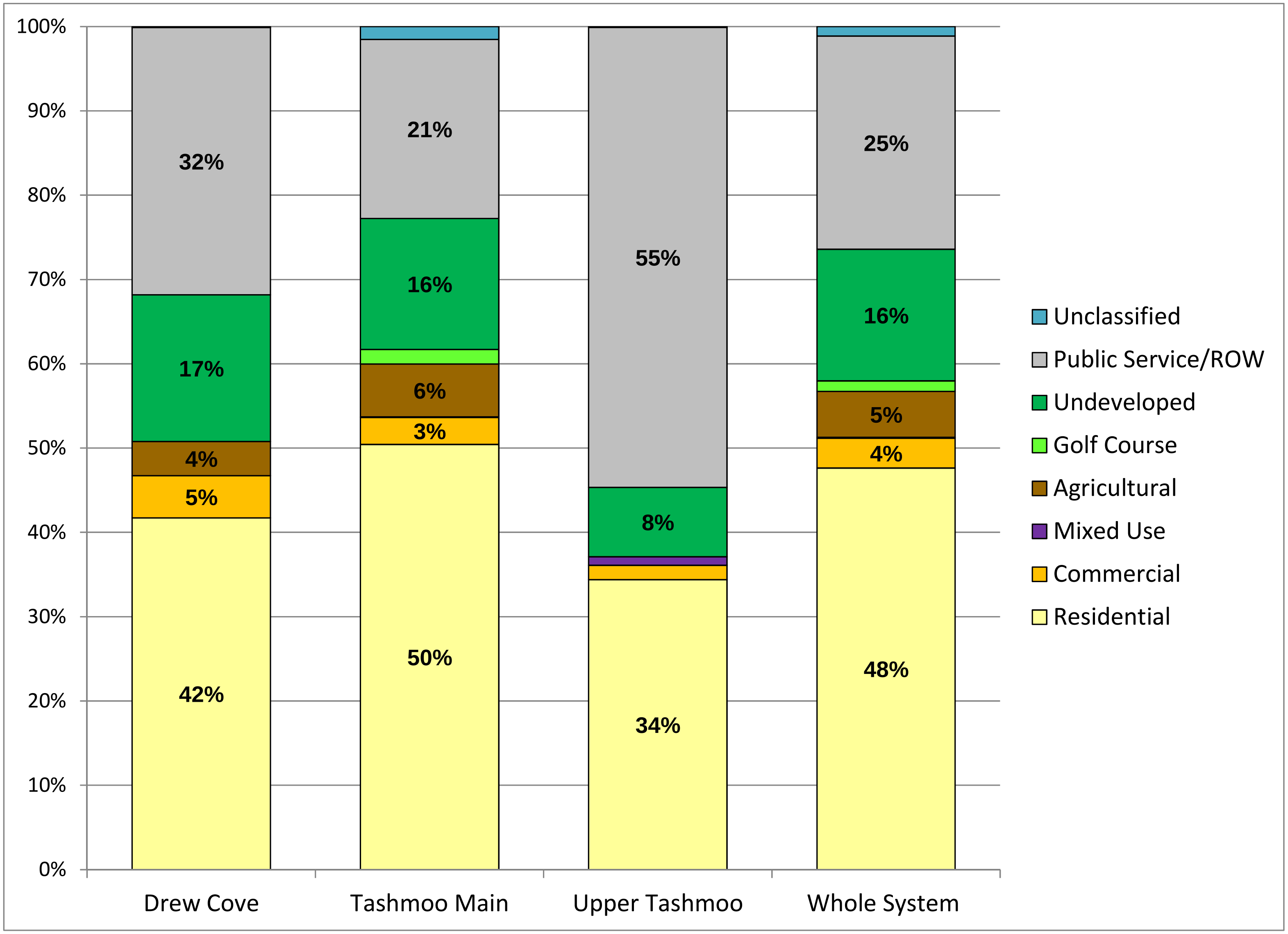

Figure IV-2. Distribution of land-uses by area within each sub-watershed and whole watershed to the Lake Tashmoo Estuary. Only percentages greater than or equal to 3% are shown. Land use categories are based on town assessor and Massachusetts DOR (2012) classifications.

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

All nitrogen losses within the septic system are incorporated into the MEP analysis. For example, information developed at the 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). Downgradient studies of septic system plumes indicate that further nitrogen loss during aquifer transport is negligible (Robertson *et al*. 1991, DeSimone and Howes 1996).

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

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

While census-based population data has limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water use based on average residential occupancy to measured average water uses. This is performed as a quality assurance check to increase certainty in the final results. This comparison has shown that the larger the watershed area the better the match between average water use and census based 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, both of which cover 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 small areas of any given town, have shown up to a 13% difference in average occupancy from town-wide occupancy rates. These analyses provide additional support for the use of the water use approach in the MEP study region.

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

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

In order to provide an independent validation of the average residential water use within the Lake Tashmoo watershed, MEP staff reviewed US Census population values for the towns of Tisbury, West Tisbury, and Oak Bluffs. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that a bedroom has 2 persons and an associated 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 Tisbury, West Tisbury, and Oak Bluffs was 2.19, 2.29, and 2.28 people per housing unit, respectively. Year-round use of the total housing units in each of the towns was 58%, 54%, and 46%, respectively. Occupancy and year-round use generally decreased from 2000 Census values except for Oak Bluffs year-round use, which increased slightly from 42% in the 2000 Census to 46% in the 2010 Census.

In order to provide a check on the measured water use, the 2010 Census average occupancies in each of the towns were combined with the state Title 5 estimate of 55 gpd of wastewater *per capita* to estimate average wastewater flows. The estimated flows based on this approach were 120 gpd, 126 gpd, and 125 gpd for residences within Tisbury, West Tisbury, and Oak Bluffs, respectively. MEP assessments typically multiply year-round occupancy by two or three to account for summer population additions (assumed to occur for three months). The average measured water use for single-family residences in the Lake Tashmoo watershed (190 gpd) is best matched by assuming a summer population three times the annual year-round population. A summer population three times the year-round population is roughly equivalent to occupying all the seasonal homes and increasing the occupancy by one person (*e.g.*, increasing occupancy in Tisbury from 2.19 to 3.28 people per dwelling annualized). With this tripling of population during the summer, the respective estimated average annual water use per residence in the three towns are 180 gpd, 189 gpd, and 188 gpd, respectively. Since it is reasonable to assume that summer populations triple year-round populations, this analysis suggests that population and water use information are in reasonable agreement and that the average <u>measured</u> water use is reasonably reflective of average wastewater estimates.

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

Water use information exists for 52% of the 994 developed parcels in the Lake Tashmoo watershed. Parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (*e.g.*, 101 or 325) and have been confirmed as having buildings on them through a review of aerial photographs, but do not have a listed account in the water use databases. Of the 473 developed parcels without water use accounts, 341 (72%) are classified as single-family residences (land use code 101). These parcels are assumed to utilize private wells and are assigned the Lake Tashmoo MEP watershed average water use of 190 gpd in the watershed nitrogen loading modules. Another 64 developed parcels without water use are parcels classified as other types of residential properties (*e.g.*, multi-family or condominiums). These parcels are assumed to utilize private wells and are assigned the Lake Tashmoo MEP watershed average water use of 510 gpd and 467 gpd for parcels assigned the 104 (two family residences) and 109 (multi-family residences) land use codes, respectively.

Water use estimates for commercial and industrial properties were treated in a similar manner. Project staff reviewed the site-specific information for each commercial and public service parcels (land uses classified in the 300 and 900 groups, respectively), including water use, building size, and lot size. For properties without metered water use information, staff developed a watershed-specific water use factor based on a water use per building average square footage derived from information within the Lake Tashmoo watershed. Commercial buildings with water use within the Lake Tashmoo watershed were found to use an average of 65.7 gpd per 1,000 sq ft of building area. Since building areas were available for all properties within the watershed, project staff used this factor to determine site-specific water use for all properties without metered water use or other site-specific water use information.

Wastewater Treatment Facilities

When developing watershed nitrogen loading information, MEP project staff typically seeks additional information on enhanced wastewater treatment, including wastewater treatment facilities (WWTFs), in the project study area. This information is reviewed and if judged reliable is included in the watershed nitrogen loading model. Typically, this includes review of treatment facilities with MassDEP groundwater discharge permits (GWDP). A GWDP is required under MassDEP regulations for wastewater treatment systems with design flows greater than 10,000 gallons per day. The Town of Tisbury WWTF is the only WWTF currently discharging within the Lake Tashmoo watershed.

The Town of Tisbury WWTF treats wastewater collected from areas outside of the Lake Tashmoo watershed. The treated effluent is discharged at two sites, one of which is located along the eastern watershed boundary of Lake Tashmoo. MVC staff provided performance data on the Tisbury WWTF, including 2007-2009 effluent flows and effluent total nitrogen concentrations (Figure IV-3). Review of this data shows an average effluent discharge flow of 35,944 gpd with an average effluent TN concentration of 4.2 mg/L. Staff also reviewed the monthly mass of total nitrogen discharge and determined that the WWTF discharged an annual average of 215 kg of nitrogen.

Staff then reviewed the two locations of the effluent discharge utilized by the WWTF and determined that one of the sites is outside of the Tashmoo watershed and the other is ~80% within the watershed. Given the sensitivity of groundwater flowpaths to large discharges, it is likely that the portion of the boundary discharge area within the watershed varies depending on the volume of effluent discharge. In order to simplify the nitrogen loading analysis, staff assumed that the portion of the WWTF effluent discharged at this site is all discharged within the Lake Tashmoo watershed. This assumption is consistent with MassDEP guidance to be more conservative in cases where uncertainty exists. The net result is that for the MEP assessment, the Tisbury WWTF is assumed to discharge 107 kg/yr within the Lake Tashmoo watershed.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilizers, including fertilized lawns, agricultural land uses (including cranberry bogs), and golf courses. Among these, residential lawns are usually the predominant watershed source within this category. In order to add all of these sources to the nitrogen-loading model for the watershed to Lake Tashmoo, project staff reviewed available information about residential lawn fertilizing practices within the Lake Tashmoo watershed and agricultural fertilizer usage within other estuary watersheds on Martha's Vineyard. There are no cranberry bogs within the Lake Tashmoo 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 prior to the MEP, 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. This effort, which was completed prior to the start of the MEP, accounted for proximity to fresh ponds and estuarine waters. 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 commercial fertilizer bags. Integrating the average residential fertilizer application rate with a leaching rate of 20% results in an average 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.

MVC has reviewed lawn areas within the Lake Tashmoo watershed in two separate assessments: 2003 and 2010 (personal communication, Bill Wilcox, MVC). In 2003, the average fertilized lawn area was 2,600 sq ft, while it was 2,989 sq ft in 2010. These assessments reviewed the area of turf on each parcel and then made a determination of the area of fertilized turf. MVC also determined fertilized turf areas on selected parcels by review of aerial photographs. In the Lake Tashmoo Watershed Nitrogen Loading Model, fertilized lawn areas were assumed to be 2,989 sq ft unless site-specific areas had been determined. Other lawn loading factors in the Lake Tashmoo model are those generally used in MEP nitrogen loading calculations.

The Lake Tashmoo watershed also includes portions of the Mink Meadows Golf Course. Project staff attempted to contact a course representative to determine course-specific fertilizer nitrogen applications, but was unsuccessful. MVC GIS staff determined fairway/rough, green, and tee areas within the watershed based on a review of aerial photographs. Nitrogen loads for each turf area were then based on average application rates determined from 23 other golf courses in the MEP study region that have provided course-specific fertilizer application rates. Based on this data, the average nitrogen application rates used for the Mink Meadows Golf Course are: 3.5 lbs/1,000 sq ft for greens, 3.5 lbs/1,000 sq ft for tees, and 3.2 lbs/1,000 sq ft for fairways. Application rates for rough areas are typically lower (2.4 lbs/1,000 sq ft average over the 23 available courses) than fairways, but review of historic aerial photographs available through Google Earth suggested some of the potential rough areas were sometimes treated as fairways in the recent past. MEP staff decided to conservatively treat all potential rough areas as fairways. This assumption is consistent with MassDEP guidance to be more conservative in cases where uncertainty exists. Overall, the set of assumptions means that Mink Meadows Golf Course adds 139 kg/yr of nitrogen to the Lake Tashmoo watershed.

Nitrogen Loading Input Factors: Agricultural Areas

Working with MEP staff, MVC staff also reviewed all parcels classified as agricultural land uses (700s MADOR codes), as well as agricultural activities on other non-farm classified properties. The area of fertilized crops was determined and counts for farm animals were obtained. Standard MEP agricultural crop and farm animal nitrogen loading factors that have been developed for use in other MEP analyses on Martha's Vineyard were used within the Lake Tashmoo watershed to determine parcel-specific loads. According to this review and application of the MEP factors, the watershed has 71 acres of cropland and crop fertilizers on these lands add 179 kg/yr of nitrogen to the Lake Tashmoo watershed. MVC staff also provided farm animal counts within the watershed (personal communication, Bill Wilcox, MVC, 6/11). This review identified 228 animals with chickens (88%) being the most common. MEP nitrogen loading factors that have previously been developed for farm animals, including nitrogen leaching rates and species-specific total nitrogen releases, were used to develop parcel-specific farm animal nitrogen loads. According to this review, the counted farm animals add 277 kg/yr of nitrogen to the overall Lake Tashmoo watershed.

Nitrogen Loading Input Factors: Town of Tisbury Landfill and Septage Lagoon

MEP staff reviewed MassDEP's solid waste database and identified one solid waste site within the Lake Tashmoo watershed: the Town of Tisbury Landfill. The Town landfill is located south of High Point Lane within the Lake Tashmoo Main sub-watershed (sub-watershed #2). According to MassDEP records, the landfill is ~10 acres, unlined, began accepting municipal solid waste in 1920 and was closed in 1994. A now closed septage lagoon (~2.5 acres) is adjacent to the landfill cells. Both the landfill and the septage lagoon are now capped. Water quality monitoring and water level data are collected twice a year from six wells located around the combined site. MVC and MEP staff obtained water quality monitoring data from 11 compliance sampling rounds (December 2004 through November 2009) for the landfill and 9 sampling rounds (May 2005 to May 2007) for the septage lagoons (monitoring well MW-1). Using the available monitoring information, MEP staff developed a nitrogen load for the landfill site.

MEP staff reviewed the chemical data, well construction details, depths, and locations to determine nitrogen loads for both the landfill and the septage lagoons. Groundwater monitoring data includes nitrate-nitrogen, total dissolved nitrogen, alkalinity, chloride, and other inorganic measures. Staff relied on the total dissolved nitrogen concentrations and focused on the two wells (106s and 107d) that appear, based on monitoring data, to be in the primary down-gradient flow path. Water table readings at the site suggest a relatively flat water table across the site, which would be consistent with the landfill's location near the groundwater divide between Lagoon Pond and Lake Tashmoo. The review of available monitoring data resulted in the following average total dissolved nitrogen concentrations: 0.99 mg/L for the landfill and 3.69 mg/L for the septage lagoons. Using these concentrations, the area of solid waste and the septage lagoons, and the MEP recharge rate for the area, MEP staff was able to estimate an annual total nitrogen load of 29 kg from the Tisbury landfill and 27 kg for the septage lagoons.

A more refined evaluation and assessment of the established landfill monitoring well network, including, at a minimum, analysis of water table fluctuations and flow directions, would help to refine this assessment and future management options. However, a more detailed assessment of all the available data is beyond the scope of the MEP. Staff balanced reasonable estimates of the various factors based on the general MEP guidance from MassDEP to include conservatism in nitrogen loading estimates when uncertainty exists in the data.

Nitrogen Loading Input Factors: Other

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

Table IV-1. Primary Nitrogen Loading Factors used in the Lake Tashmoo MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific and Martha's Vineyard factors are derived from watershed- and island-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[6]	1.09	Water Use/Wastewater:[3]	
Natural Area Recharge	0.072	Existing and buildout single family residences (land use code 101)	190 gpd
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (sq ft)[1]	2,989	Two-family residential (land use code 104)	510 gpd
Residential Watershed Nitrogen Rate (lbs/1,000 sq ft)[1]	1.08	Multiple houses on same lot residential (land use code 109)	467 gpd
Nitrogen leaching rate	20%	Existing and buildout commercial and public service parcels with buildings and no metered water use (gpd/sq ft of building)	0.066
Building area based on individual building measures		Guesthouses (added at buildout to existing single family residences)	85 gpd
Farm Animals[4]	kg/yr /animal	Tisbury Wastewater Treatment Facility	
Horse	32.4	Effluent TN concentration (mg/L)	4.18
Sheep	7.3	Average annual flow (gpd)	35,944
Chickens	0.4	Crops[4]	kg/ha/yr
Animal N leaching rate	40%	Hay, Pasture, Nursery[5]	5
		Row Crop	34
		Crop N leaching rate	30%

Notes:

1) This is the average area determined by MVC staff from measurement of lawns in the Lake Tashmoo watershed in 2010.
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) Water use was available for portions of Tisbury and Oak Bluffs. Values presented are averages from corresponding land uses within the Lake Tashmoo watershed.
4) Crop and farm animal loading rates and leaching rates are standard MEP factors based on available literature and USDA guidance.
5) Hay, pasture, and nursery loading rate incorporates leaching rate.
6) Monitoring and modeling completed in the Chesapeake watershed (Schwede and Lear, 2014), which would be the origin land area for Vineyard and Cape Cod air most of the year had N deposition rates of 10.2 to 11.8 kg/ha/yr. Although the MEP does not go into extensive detail in the atmospheric deposition, the comparable MEP rate on the Vineyard would be 12.98 kg/ha/yr with 11.07 kg/ha/yr on the Cape. The Vineyard rate is higher because it receives more precipitation than the Cape.

IV.1.3 Calculating Nitrogen Loads

Once all the land use and water use information was linked to the parcel coverages, nitrogen loads from individual parcels were assigned to various watersheds based initially on whether nitrogen load source areas were located within a respective watershed. These initial assignments were then refined by reviewing individual parcels straddling watershed boundaries including corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Individualized information for parcels with atypical nitrogen loading (farm animals, agricultural fields, etc.) was also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure for boundary parcels generally would have a negligible effect on the overall nitrogen loading to the Lake Tashmoo estuary or its sub-watersheds. The assignment effort was undertaken to better define the sub-embayment loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Following the assignment of all parcels to sub-watersheds, all relevant nitrogen loading data were also assigned by sub-watershed. This step includes summarizing water use, parcel area, turf area, private wells, and road area. Individual sub-watershed information was then integrated to create the Lake Tashmoo Watershed Nitrogen Loading model with summaries for each of the individual sub-watersheds. The sub-watersheds generally are paired with functional embayment/estuary units for the Linked Watershed-Embayment 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 Lake Tashmoo System, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), the Tisbury WWTF discharge, the Tisbury landfill and septage lagoon, turf fertilizer (including residential lawns), agricultural fertilizers, farm animals, impervious surfaces (including roads and roofs), direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of each component sub-embayment partitioned among each of the source categories (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 through streams or ponds, if any. These attenuated loads reach the estuarine waters and are used in the embayment water quality sub-model.

Freshwater Pond Nitrogen Loads

Freshwater ponds in the Martha's Vineyard eco-region are generally watershed sites of natural nitrogen reduction (or attenuation) prior to the watershed nitrogen reaching an estuary. These fresh ponds are generally kettle hole depressions of the land surface that intercept the surrounding groundwater table revealing what some call "windows on the aquifer." Groundwater typically flows into the pond along the 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, which is often a herring run, that also acts as a discharge point or will have their water level artificially manipulated through the use of a dam or weir. These changes to a typical kettle hole pond configuration alter the residence time of water within the pond and can also alter the nitrogen attenuation of the pond ecosystem. Since the nitrogen loads usually flow into a pond with the groundwater, the relatively more productive pond ecosystems incorporate some of the nitrogen, retain some nitrogen in the sediments, and

Table IV-2. Lake Tashmoo Watershed Nitrogen Loads. Present nitrogen loads are based on current land use conditions, including agricultural land uses within the watershed. Buildout loads include septic, fertilizer, and impervious surface additions from properties classified as developable by the town assessors and include conversion of lands currently used for agriculture, but classified by the towns as residential properties. No attenuation assigned to the load out of Upper Lake Tashmoo based on measured data collected at its outlet to Drew Cove (see Section IV.2). All loads are kg N yr^{-1}.

		Tashmoo Pond N Loads by Input (kg/yr):										Present N Loads			Buildout N Loads		
Name	Watershed ID#	Wastewater	WWTF	Landfill	Turf Fertilizers	Agricultural Fertilizers	Agricultural Animals	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Tashmoo Pond System Total		6,861	107	56	457	179	277	715	1,398	502	4,040	10,553		10,553	14,593		14,593
Drew Cove	1	1,053	-	-	38	52	243	112	-	121	478	1,618	0%	1,618	2096	0%	2,096
Tashmoo Main	2	5,627	107	56	411	127	-	581	-	356	3,510	7,266	0%	7,266	10776	0%	10,776
Upper Tashmoo	3	181	-	-	8	-	34	22	7	26	52	279	0%	279	331	0%	331
Drew Cove Estuary Surface									184			184		184	184		184
Tashmoo Estuary Surface									1,206			1,206		1,206	1206		1,206

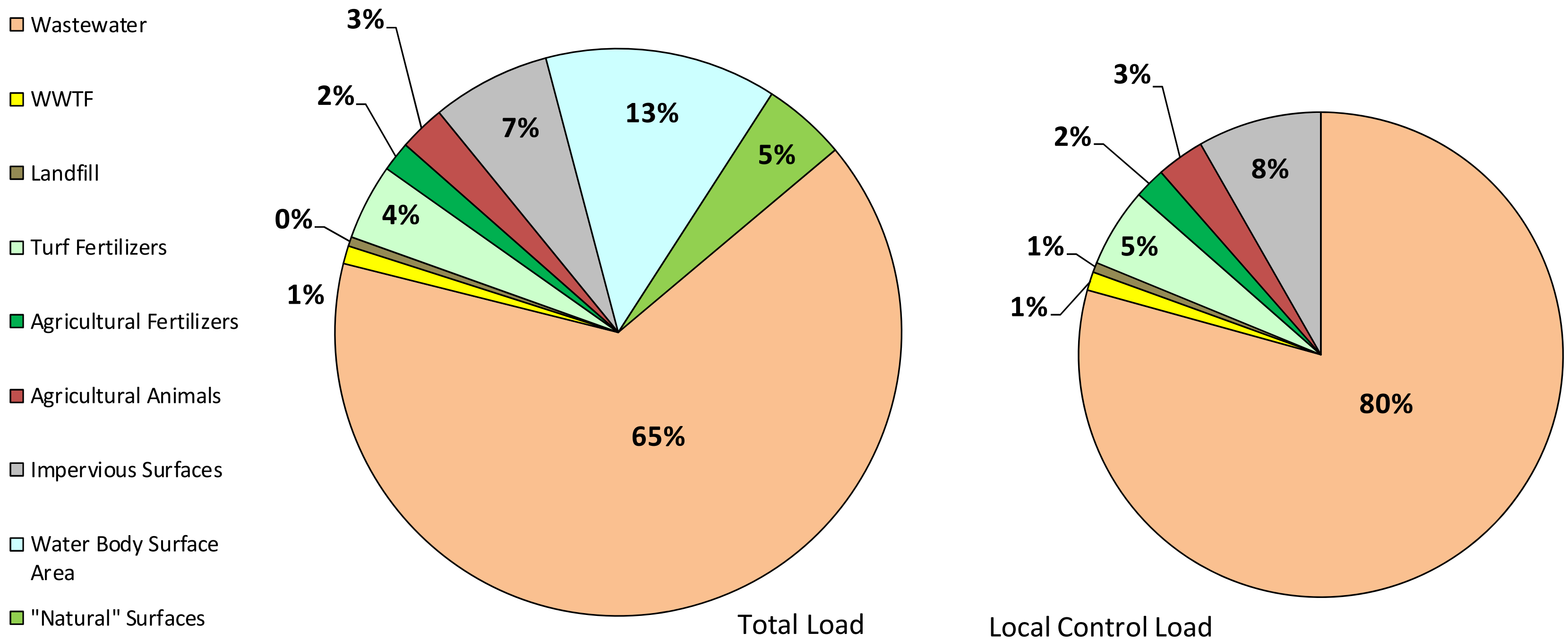

Figure IV-3. Unattenuated nitrogen load for land use loading categories as percent of total nitrogen loading within the overall Lake Tashmoo Estuary watershed. “Overall Load” is the total nitrogen input within the watershed, while the “Local Control Load” represents only those nitrogen sources that could potentially be under local regulatory control.

change the nitrogen among its various oxidized and reduced forms. As result of these interactions, some of the nitrogen in the pond watershed is removed from the watershed system prior to reaching the estuary. The removal processes are mostly through burial in pond sediments and denitrification within the surficial pond sediments that returns a portion of the remineralized nitrogen to the atmosphere. Following these reductions, the remaining (attenuated) nitrogen load flows back into the groundwater system along the down-gradient side of the pond and eventually is discharged into the down-gradient estuary or through a stream outlet directly to the estuary. The nitrogen load summary in Table IV-2 includes both the unattenuated and attenuated nitrogen load to each sub-watershed.

Nitrogen attenuation in freshwater ponds has generally been found to be at least 50% in MEP analyses, so a conservative attenuation rate of 50% is generally assigned to all nitrogen from freshwater pond watersheds in the watershed model unless more detailed pond monitoring or studies are available. Detailed studies of other southeastern Massachusetts freshwater systems including Ashumet Pond (AFCEE, 2000) and Agawam/Wankinco River Nitrogen Discharges (CDM, 2001) have supported a 50% attenuation factor as a reasonable, somewhat conservative rate. However, in some cases, if sufficient monitoring information is available, a pond-specific attenuation rate is incorporated into the watershed nitrogen loading modeling [*e.g.*, 87%, Mystic Lake; 40%, Middle Pond; and 52%, Hamblin Pond in the Three Bays MEP Report (Howes, *et al.*, 2006)]. In order to review whether a pond-specific nitrogen attenuation rate other than 50% should be used, the MEP Technical Team reviews the available data on each pond, including available nitrogen concentrations, impacts of sediment regeneration, temperature profiles, and bathymetric information.

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

In addition to bathymetry, temperature profiles are useful to help understand whether temperature stratification is occurring in a pond. If the pond has an epilimnion (*i.e.*, a well-mixed, relatively warm isothermic, 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 location in the pond for watershed nitrogen loads; the deeper hypolimnion generally has limited interaction with the upper layer during stratification. However, impaired conditions in a deeper hypolimnion can result in significant sediment regeneration of nitrogen. In these lakes/ponds, regenerated sediment nitrogen can filter into the upper layer and impact measured nitrogen concentrations. For this reason, water quality conditions in the ponds should also be considered when estimating nitrogen attenuation, if appropriate data is available.

Upper Lake Tashmoo is a small freshwater pond (spring) within the overall Lake Tashmoo study area. Based on review of available sources, it does not appear that the pond itself has been monitored, but regular monitoring of its outlet has occurred (see Section IV.2). This data shows that the estimated watershed nitrogen load is approximately the same as the measured load at the pond outlet. Because these loads are essentially the same, no natural nitrogen attention was assigned to Upper Lake Tashmoo. While this is somewhat unique, low or no attenuation rates in ponds or streams have been measured in other MEP assessments [*e.g.*, Mill Pond in Three Bays (Howes, *et al*., 2006)]. Typically ponds with no or low nitrogen attenuation rates are shallow and have very short residence times. They are often mill ponds that have accumulated stream sediments and lost volume over the course of many centuries.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment (or scenario) of potential development and accompanying nitrogen loads within the study area watersheds. The MEP buildout scenario development is relatively straightforward and is generally completed in four steps: 1) each residential parcel classified by the town assessor as developable is identified and divided by minimum lot sizes specified in town zoning and the resulting number of new residential units is rounded down, 2) parcels classified as developable commercial and industrial parcels by the town assessor are identified, 3) residential, commercial and industrial parcels with existing development and areas greater than twice zoning's minimum lot size are identified, divided by the minimum lot size and the resulting number of new units is rounded down, and 4) results are discussed with town staff and/or planning board members and the analysis results are modified based on local knowledge. Project staff typically reviews these initial results with local experts, who were MVC staff in this case, to produce a final integrated MEP buildout assessment.

It should be noted that the initial MEP buildout approach is relatively simple and does not include any modifications/refinements for lot line setbacks, wetlands, road construction, frontage requirements, parcel shape requirements, or other more detailed zoning provisions. The MEP buildout approach also does not include potential impacts associated with the higher densities usually associated with 40B affordable housing projects. The fourth step, including the discussions with local planners and occasionally, local planning boards and wastewater consultants, usually leads to additional insights on developments that are planned (e.g. developments planned on government or public service parcels and updates to assessor classifications, including lands purchased by the town as open space). This final step can lead to removal and/or additions to the number of parcels initially identified as developable and the application of more detailed zoning provisions.

As an example of how the MEP approach might apply, assume an 81,000 square foot lot is classified by the town assessor as a developable residential lot (MassDOR land use code 130). This lot is divided by the 40,000 square foot minimum lot size specified in town zoning and the result is rounded down to two. As a result, two additional residential lots would be added to the sub-watershed in the MEP buildout scenario. This addition could then be modified during discussion of local staff.

Other provisions of the MEP buildout assessment include town assessor classification of undevelopable lots, standard treatment of commercial and industrial properties, and assumptions for lots less than the minimum areas specified by zoning. Properties classified by the Town of Tisbury, Oak Bluffs, or West Tisbury assessors as "undevelopable" (*e.g.*, MassDOR codes 132, 392, and 442) are not assigned any development at buildout (unless revised by the local review). Commercial properties classified as developable are not subdivided; the area of each parcel and the factors in Table IV-1 are used to determine an estimated building size and wastewater flow for these properties. This process would also apply to industrial properties, but there are no industrial properties classified as developable in the Lake Tashmoo MEP watershed. Pre-existing lots classified by the town assessor as developable are also treated as developable even if they are less than the minimum lot size specified in zoning; so, for example, a 10,000 square foot lot classified by the town assessor as a developable residential property (MassDOR 130 land use code) and located in a zoning area with a 40,000 square feet minimum lot size will be assigned an additional residential dwelling in the MEP buildout scenario. Most town zoning bylaws have a lower minimum lot size for pre-existing lots (usually 5,000 square feet) that will minimize instances of regulatory takings. Existing developed residential properties that are larger than zoning's minimum lot sizes are also assigned additional development potential only if enough area is available to accommodate at least one additional lot as specified by the zoning minimum.

For the Lake Tashmoo Estuary buildout assessment, MVC staff under the guidance of MEP staff reviewed individual properties for potential additional development. This review included assessment of minimum lot sizes based on current zoning and potential additional development on existing developed lots. Based on this buildout assessment, there are 494 potential additional single-family residential dwellings, 124 potential future guesthouses, and 36 acres of developable commercial properties within the Lake Tashmoo watershed. No future industrial development is assumed in the watershed because there are no lands classified as developable industrial properties. All parcels included in the buildout assessment of the Lake Tashmoo watershed are shown in Figure IV-4.

Nitrogen loads were developed for these buildout additions based largely on existing development factors within the Lake Tashmoo watershed. Additional buildout single-family residential dwellings were assigned a water use flow of 190 gpd, which is the same measured average water use assigned to developed residences in the watershed without metered water use. The Town of Tisbury WWTF is conservatively assumed to increase its flow to its design flow while maintaining its current effluent TN concentration. Other factors used in the MEP buildout assessment are listed in Table IV-1.

Many of the parcels assigned additional development at buildout already have agricultural uses (*e.g.*, parcels assigned as developable residential parcels by the town assessor, but currently being used as pasture or for hay). Existing agricultural loads were removed if the parcel was identified as having additional residential development in the buildout scenario. It should be noted that the MEP buildout is only one example of a buildout scenario; alternative assumptions about future development could be developed to assess the water quality impacts of other buildout scenarios as needed.

Table IV-2 presents a sum of the additional nitrogen loads by sub-watershed for the MEP buildout scenario. This sum includes the wastewater, fertilizer, and impervious surface loads from additional residential dwellings and commercial properties. Overall, MEP buildout additions within the entire Lake Tashmoo System watershed will increase the unattenuated loading rate by 38%.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

IV.2.1 Background and Purpose

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out, sewering analysis, enhanced flushing, pond/wetland restoration for natural attenuation, etc.) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of

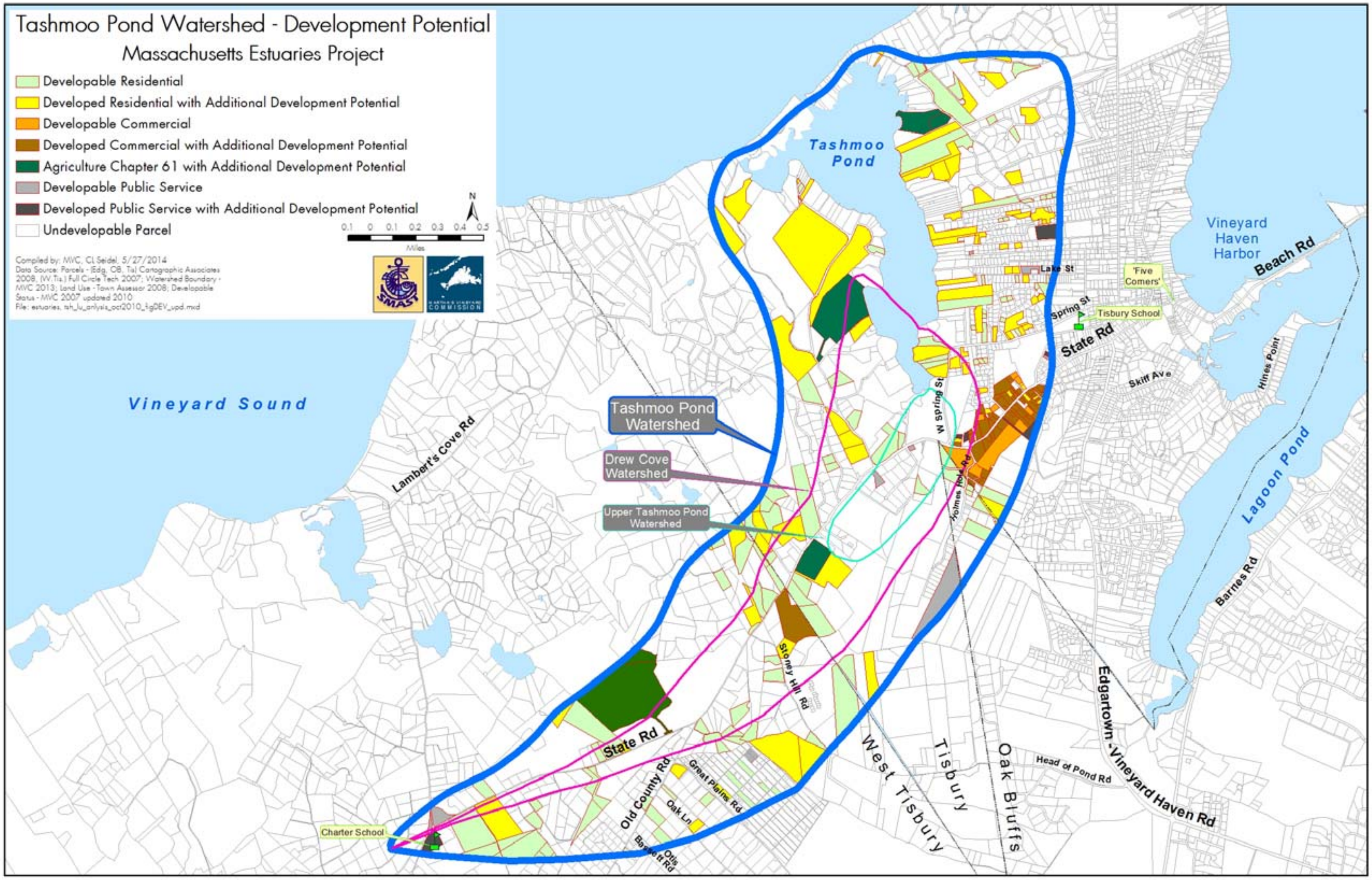

Figure IV-4. Developable Parcels in the Lake Tashmoo watershed. Developable parcels and developed parcels with additional development potential are highlighted. The parcels are selected based on town assessors' land use classifications and review of minimum lot sizes in town zoning regulations. Nitrogen loads in the MEP buildout scenario are based on additional development assigned to these parcels.

estuarine systems. Rates of nitrogen loading to the sub-watersheds of the Lake Tashmoo Estuary 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 Lake Tashmoo 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, 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 Lake Tashmoo Estuary, a portion of the watershed derived freshwater flow and associated nitrogen load passes through a surface water system prior to discharging to the headwaters of the estuary. The surface water system consists of a groundwater fed spring that forms a small pond at the head of the system (a small freshwater pond known by the Wampanoag Indians as Kuttashimmo {great spring}). The small pond drains through a small surface water discharge via a fish ladder (for anadromous fish passage) directly into the headwaters of the Lake Tashmoo Estuary. This surface freshwater system provides the potential for nitrogen removal (attenuation) during transport from watershed to estuary.

Failure to account for any naturally occurring attenuation of watershed derived nitrogen overestimates the nitrogen load to receiving estuarine waters. The distribution of nitrogen attenuation also has significant nitrogen management implications. 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, in a preliminary study of Great, Green and Bournes Ponds in Falmouth, measurements indicated a 30% attenuation of nitrogen during stream transport (Howes and Ramsey 2001). An example where natural attenuation played a significant role in nitrogen management can be seen relative to West Falmouth Harbor (Falmouth, MA), where ~40% of the nitrogen discharge to the Harbor originating from the groundwater effluent plume emanating from the WWTF was attenuated by a small salt marsh prior to reaching Harbor waters. Clearly, proper development and evaluation of nitrogen management options requires determination of the nitrogen loads reaching an embayment, not just loaded to the watershed.

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP analysis of the Lake Tashmoo Estuary. MEP conducted long-term measurements of natural attenuation relating to the small spring fed pond at the head of Lake Tashmoo and its discharge to the estuarine reach of the Lake Tashmoo system. Additional evaluation of attenuation in other surface water features in the watershed such as fresh kettle ponds (Section IV.1) was undertaken based on the availability of pond specific data. The sampling and analysis of the spring fed pond was conducted at the fish ladder (Figure IV-5), as the outflow provided a suitable location where freshwater flows could be measured and samples taken to determine the nitrogen load to the estuary.

Quantification of surface water 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 the associated contributing area 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 various gauging sites. Flow and nitrogen load were measured at the gauge at the freshwater “stream” site for a total of 18 months of record (Figures IV-6). During the study period, velocity profiles were completed every month to two months. The summation of the products of channel subsection areas of the fish ladder cross-section and the respective measured velocities represent the computation of instantaneous stream flow (Q).

Determination of the outflow from spring pond via the fish ladder at the gauge was calculated and based on the measured values obtained for channel cross sectional area and velocity. Discharge from the fish ladder to the estuarine reach of Lake Tashmoo was represented by the summation of individual discharge calculations for each channel subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire channel cross section were not averaged and then applied to the total channel cross sectional area.

The formula that was used for calculation of flow (discharge) from the fish ladder is as follows:

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

where by:

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

Thus, each channel subsection will have a calculated discharge value and the summation of all the sub-sectional discharge values will be the total calculated discharge for the fish ladder connecting spring at the head of the system to the estuarine reach of Lake Tashmoo.

Periodic measurement of flows over the entire 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 water level gauge deployed in the fish ladder. Water level data obtained every 10-minutes was averaged to obtain hourly stages in the fish ladder. These hourly stage values were then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. In the case of tidal influence on stage in the fish ladder, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of strictly freshwater flow. The two low tide stage values for any given day were averaged and the average stage value for a given day was then entered into the stage – discharge relation in order to compute daily flow. A complete annual record of freshwater flow through the fish ladder (365 days) was generated for the surface water discharge flowing into the Lake Tashmoo Estuary from up-gradient spring fed pond.

Figure IV-5. Location of the stream gauge (red symbol) in the Lake Tashmoo embayment system. The site is an anadromous fish run, with a constructed fish ladder.

The annual flow record for the surface water flow at the gauge was merged with the nutrient data set generated through the weekly water quality sampling performed at the gauge location to determine nitrogen loading rates to the head of the Lake Tashmoo Estuary. Nitrogen discharge from the fish ladder was calculated using the paired daily discharge and daily nitrogen concentration data to determine the mass flux of nitrogen through the gauging site. For the gauge location, weekly water samples were collected (at low tide for a tidally influenced stage) in order to determine nutrient concentrations from which nutrient load was calculated. Unfortunately, there was an approximately 4 month period during the hydrologic year when nutrient samples were not collected thus creating a gap in the water quality data set at the Lake Tashmoo gauge. It was therefore necessary to calculate an average daily water quality concentration based on the months for which samples were collected. The average nutrient concentration values based on all the samples collected was paired with the flows during the months when samples were not collected in order to calculate an estimate of nutrient load for a complete year. With the exception of the period of time when samples were not collected, 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 flow through the fish ladder 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 the gauged "stream" currently reduces (percent attenuation) nitrogen loading to the overall embayment system.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Fish Ladder Connecting Freshwater Spring to Estuarine Reach of Lake Tashmoo

The freshwater spring fed pond, located at the head of the Lake Tashmoo Estuary, is an artificially created freshwater pond with a surface water discharge via a fish ladder to the estuary. A MEP stream gauge was established at the discharge to the estuary. Unlike many of the freshwater ponds on Cape Cod, this pond has a fresh surface water outflow rather than discharging solely to the aquifer along its down-gradient shore. This "stream" outflow, the fish ladder, 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. The combined rate of nitrogen attenuation by natural processes occurring in both the watershed and the pond was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to spring fed pond above the gauge site and the measured annual discharge of nitrogen to the tidal portion of the Lake Tashmoo system, Figure IV-5.

At the Lake Tashmoo gauge site, a continuously recording vented calibrated water level logger (gauge) was installed to yield the level of water in the freshwater portion of the fish ladder connecting the up-gradient spring fed pond to the upper estuarine reach of Lake Tashmoo. This fish ladder carries the flows and associated nitrogen load to the Lake Tashmoo Estuary, which then flushes to the near shore waters of Vineyard Sound. As the lower portion of the fish ladder is tidally influenced, the gauge was located as well as possible in the fish ladder taking into consideration the up-gradient constraints of the structure as well as accessibility. Ultimately, the gauge was situated in a manner such that freshwater flow could be measured at low tide. To confirm that freshwater was being measured the stage record was analyzed for any semi-diurnal variations indicative of tidal influence and salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average low tide salinity was determined to be 0.1 ppt, whereas the salinity just down gradient within the estuary was 28 ppt.

Therefore, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked approximately monthly. The gauge in the fish ladder from the up-gradient spring fed pond was installed on June 9, 2003 and was set to operate continuously for at least 16 months such that a full summer season would be captured in the flow record. Stage data collection continued until January 5, 2005 for a total deployment of 18 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 Lake Tashmoo 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 estuarine reach of the Lake Tashmoo system while being reflective of the biological processes occurring in the spring fed pond as well as any small ponds in the watershed (Figure IV-6 and Table IV-3). In addition, a water balance was constructed based upon the U.S. Geological Survey reviewed groundwater flow model discussed in Section III to determine long-term average freshwater discharge expected at the gauge site.

The annual freshwater flow record for the fish ladder as measured by the MEP was compared to the long-term average flows determined by the watershed modeling effort (Table III-1). The measured freshwater discharge from the fish ladder was 16% 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 873 m^3/day. Taking into consideration that precipitation during the deployment period (2003-2004) was 16% lower than the average precipitation based on data from the last 15 years, the measured flow was consistent with the long term average flows determined from a water balance of the delineated watershed to the spring fed pond (equivalent to inflow to the pond) of 1,027 m^3/day. While there may be some seepage under the rock and rubble berm that forms the actual spring fed pond, the evidence is that it is negligible. During multiple trips to the site at low tide, no significant discrete seeps were observed between the high tide and low tide marks along the ~75 foot length of the earthen berm, consistent with water exiting via the path of least resistance (i.e. surface water outflow fish ladder). Based upon the site observations and evidence from other ponds with outflows in the region, the MEP Technical Team concluded that measuring the flow through the fish ladder should capture virtually all the pond outflow. Subsequent results from the outflow measurements supported this contention, with the average measured stream flow versus modeled total sub-watershed outflow being 873 m^3/d and 1,039 m^3/d, respectively. The general agreement between measured and modeled flows, the lack of obvious high discharge seeps, and comparisons to other ponds in the region would suggest seepage under the earthen berm is insignificant. Therefore it was thought prudent to rely on the measurements unless data becomes available to indicate otherwise. The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the fish ladder supports the contention that the watershed providing flow to the herring run discharge is properly delineated.

Table IV-3. Comparison of water flow and nitrogen load discharged by the fish ladder (freshwater “stream”) connecting freshwater spring to the estuarine reach (head) of the Lake Tashmoo system. The “Stream” data are from the MEP stream gauging effort. Watershed data are based upon the MEP watershed modeling effort (Section IV.1) and the USGS confirmed watershed delineation originally developed by Whitman Howard (1994) and updated by Earth Tech.

Stream Discharge Parameter	Fish Ladder Discharge[(a)] from Freshwater Spring	Data Source
Total Days of Record	365[(b)]	(1)
Flow Characteristics		
Stream Average Discharge (m3/day)	873	(1)
Contributing Area Average Discharge (m3/day)	1,039	(2)
Discharge Stream 2003-04 vs. Long-term Discharge	16.0%	
Nitrogen Characteristics		
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.122	(1)
Stream Average Total N Concentration (mg N/L)	0.791	(1)
Nitrate + Nitrite as Percent of Total N (%)	15%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	0.69	(1)
TN Average Contributing UN-attenuated Load (kg/day)	0.764	(3)
Attenuation of Nitrogen in Pond/Stream (%)	10%	(4)

(a) Flow and N load to fish ladder discharging from freshwater spring to the estuarine reach of Lake Tashmoo, includes apportionments of Pond contributing areas.
(b) September 1, 2003 to August 31, 2004.
(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 fish ladder to Lake Tashmoo;
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 "stream" vs. the unattenuated watershed load.

Total nitrogen concentrations within the outflow from the small pond discharging to the head of Lake Tashmoo were low to moderate, averaging 0.791 mg N L^{-1}. Combining the measured flow and nitrogen levels yielded an average daily total nitrogen discharge to the estuary of 0.69 kg/day and a measured total annual TN load of 252 kg/yr. In the freshwater flowing out of the small pond through the fish ladder, nitrate made up significantly less than half of the total nitrogen pool (15%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the pond was taken up by plants within the pond and converted to organic forms (DON, PON), which are discharged through the herring ladder. Given the low level of remaining nitrate in the pond discharge, the possibility for additional nitrogen removal by direct denitrification is low. However, removal of particulate nitrogen would have a significant effect.. In addition, processes that increase denitrification prior to uptake by plants would provide a significant removal of nitrogen prior to discharge and may warrant further investigation. At present, it is not possible to give specific recommendations for increasing nitrogen removal by this fresh pond, but the present low removal rates suggest that the potential exists. Site-specific data are required to determine mechanisms for enhancing removal to the extent possible (feasibility study).

From the measured nitrogen load discharged by the pond to the head of the Lake Tashmoo estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is a low level of nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary (Table IV-4). Based upon the lower total nitrogen load (252 kg yr^{-1}) discharged from the freshwater fish ladder compared to that added by the various land-uses to the associated watershed (279 kg yr^{-1}), the integrated attenuation in passage through ponds in the watershed prior to discharge to the estuary is 10% (i.e. 10% of nitrogen input to watershed does not reach the estuary). However, as this level of attenuation is on the order of the lower flow during the study period (16%) and due to uncertainties in measured N discharge attributable to the 4 month sampling gap, zero attenuation could be assigned to the small fresh pond at this time. None-the-less the measured attenuation (10%) was consistent with other freshwater systems evaluated under the MEP with similar lack of up-gradient ponds in the watershed that would be capable of attenuating nitrogen. The modeled nitrogen load from the pond sub-watershed was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

Table IV-4. Summary of annual volumetric discharge and nitrogen load from the Fish Ladder discharge from freshwater spring to the estuarine reach of Lake Tashmoo (head of Lake Tashmoo estuarine system) based upon the data presented in Figures IV-6 and Table IV-3.

Embayment System	Period of Record	Discharge (m^3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Fish Ladder (spring pond) Upper Lake Tashmoo Discharge (MEP)	9/1/2003 – 8/31/2004	318,678	39	252
Fish Ladder (spring pond) Upper Lake Tashmoo Discharge (MEP)	Based on Watershed Area and Recharge	379,235	NA	NA

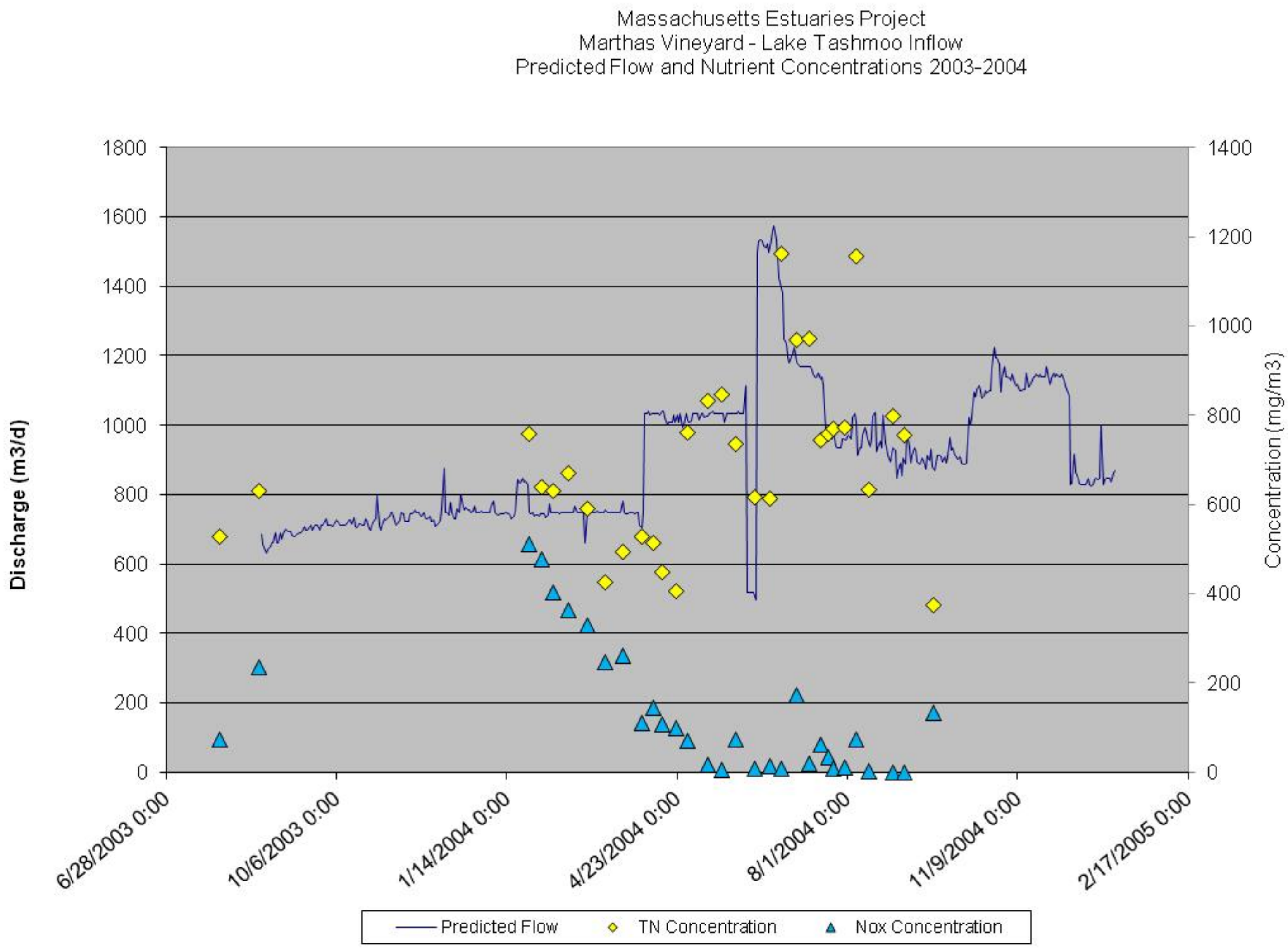

Figure IV-6. Spring discharge (solid blue line) to head of Lake Tashmoo, nitrate+nitrite (blue triangle) and total nitrogen (yellow square) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Lake Tashmoo (Table IV-6). Gap in concentration (8/21/03 to 1/26/04) due to lack of samples. Average daily concentrations for period during which samples were obtained were utilized to estimate annual load.

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

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

IV.3.1 Sediment-Water Column Exchange of Nitrogen

As stated in 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 Lake Tashmoo Estuary 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 Vineyard Sound). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom sediments. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with associated nitrogen “load” become incorporated into the surficial sediments of the system.

In general the fraction of the phytoplankton population which enters the surficial sediments of a shallow embayment: (1) increases with decreased hydrodynamic flushing, (2) increases in low velocity settings, (3) increases within enclosed tributary basins, particularly if they are deeper than the adjacent embayment. To some extent, settling characteristics can be evaluated by observation of 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 in the margins of the main basin to Lewis Bay

(Town of Barnstable, Cape Cod) or Wychmere Harbor (Town of Harwich). In contrast, regions of high deposition like Hyannis Inner Harbor in the Town of Barnstable, which is essentially a dredged boat basin, typically support anoxic sediments with elevated rates of nitrogen release during summer months. The consequence of this deposition is that these basin sediments are unconsolidated, organic rich and sulfidic nature (MEP field observations).

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the shallow waters of the lower (North Basin) and the deeper embayment basin in the upper (South Basin) will result in significant errors in determination of the threshold nitrogen loading to the overall system. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for determining sediment-water column nitrogen exchange

For the Lake Tashmoo Estuary, 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 (16) were collected from a total of 15 sites in the Lake Tashmoo system. Cores were collected from 6 sites within the upper basin (south) from the uppermost tidal reach to below Drew Cove and 9 sites in the lower portion (north) from Hillman Point to the tidal inlet to Vineyard Sound (Figure IV-7). All the sediment cores for this system were collected in August 2003. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shoreside lab (Massachusetts State Lobster Hatchery). 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-7) are as follows:

Lake Tashmoo Benthic Nutrient Regeneration Cores

- TMO-1 1 core Upper-Mid Basin (South)
- TMO-2 1 core Upper-Mid Basin (South)
- TMO-3 1 core Upper-Mid Basin (South)
- TMO-4 1 core Upper-Mid Basin (South)
- TMO-5 1 core Upper-Mid Basin (South)
- TMO-6 1 core Upper-Mid Basin (South)
- TMO-7 1 core Lower Basin (North)
- TMO-8 1 core Lower Basin (North)
- TMO-9 1 core Lower Basin (North)
- TMO-10/11 2 cores Lower Basin (North)
- TMO-12 1 core Lower Basin (North)
- TMO-13 1 core Lower Basin (North)
- TMO-14 1 core Lower Basin (North)
- TMO-15 1 core Lower Basin (North)
- TMO-16 1 core Lower Basin (North)

Figure IV-7. Lake Tashmoo embayment system sediment sampling sites (red symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above and site i.d.'s in Table IV-5.

Sampling was distributed throughout the primary component basins of the Lake Tashmoo Estuary and the results were used for calculating the net nitrogen regeneration rates for the water quality modeling effort.

Sediment-water column exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1998) for nutrients and metabolism. Upon return to the field laboratory at the Massachusetts State Lobster Hatchery on the shore of Lagoon Pond in Oak Bluffs, 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 ssampieri@umassd.edu). The laboratory follows standard methods for saltwater analysis and sediment geochemistry.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

Water column nitrogen levels are the balance of inputs from direct sources (land, rain etc), losses (denitrification, burial), regeneration (water column and benthic), uptake (e.g. photosynthesis) and losses through tidal exchange. 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 sediments of the Lake Tashmoo Estuary.

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 provide 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-8).

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 main basins of Lake Tashmoo 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 (upper and lower basins) of the Lake Tashmoo Estuary 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 main basin.

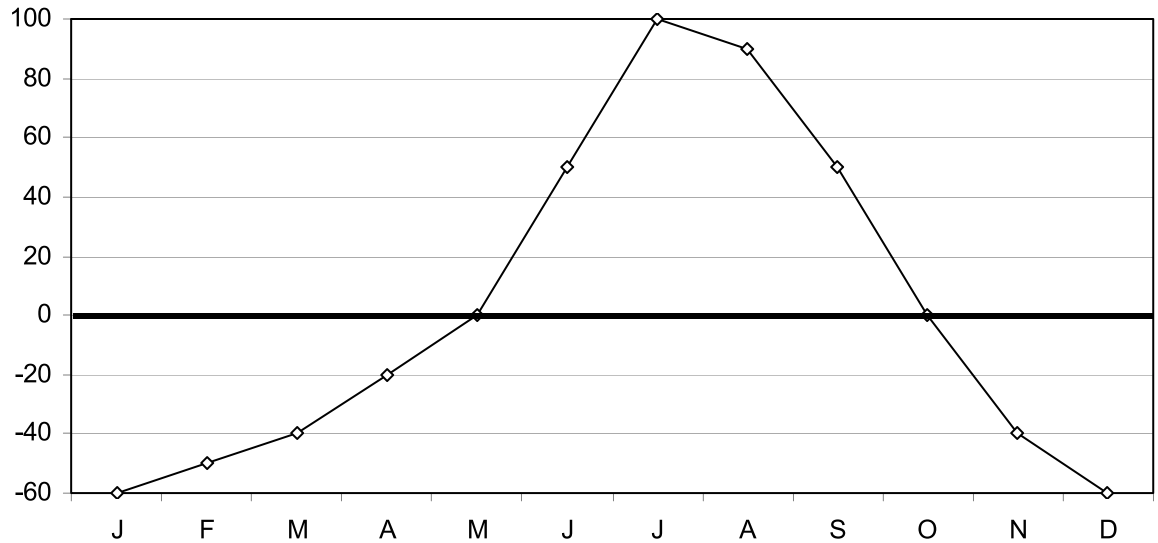

Figure IV-8. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (Chapter V). Two levels of settling are used. If the sediments were organic rich and fine grained, and the hydrodynamic data showed low tidal velocities, then a water column particle residence time of 8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins). If the sediments indicated coarse-grained sediments and low organic content and high velocities, then half this settling rate was used. Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas which are net nitrogen sinks for the aquatic system. This approach has been previously validated in outer Cape Cod embayments (Town of Chatham embayments) by examining the relative fraction of the sediment carbon turnover (total sediment metabolism), which would be accounted for by daily particulate carbon settling. This analysis indicated that sediment metabolism in the highly organic rich sediments of the wetlands and depositional basins is driven primarily by stored organic matter (ca. 90%). Also, in the more open lower portions of larger embayments, storage appears to be low and a large proportion of the daily carbon requirement in summer is met by particle settling (approximately 33% to 67%). This range of values and their distribution is consistent with ecological theory and field data from shallow embayments. Additional, validation has been conducted on 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 Lake Tashmoo embayment system were comparable to other similar embayments with similar configuration and flushing rates in southeastern Massachusetts. In addition, the spatial pattern of sediment N release was also similar to other systems, with the uppermost basin supporting the highest rates of release and diminishing rates in the lower basin moving toward the tidal inlet. The spatial pattern of sediment regeneration is consistent with the pattern of nitrogen entry into this estuary and the distribution of total nitrogen (TN) measured within the water column within those basins (Section VI). There was variability in the rates for each basin as samples were collected in patterns to purposely capture the spatial variation to adequately represent each sub-basin.

The rates of sediment-water column nitrogen exchange were consistent with other similarly configured basins functioning as open water embayments with depositional basins, as opposed to tidal rivers with extensive tidal salt marsh areas. Overall, the rates of net nitrogen release were low to moderate, 12.8 - 17.6 mg m^{-2} d^{-1} similar to the similarly structured nearby Lagoon Pond basins, 8.4 - 45.2 mg m^{-2} d^{-1}, and similar to other Nantucket Sound estuaries such as the upper reaches of the Three Bays System (North Bay to Princes Cove), 10.4 - 51.2 mg m^{-2} d^{-1} which also show declining rates toward the inlet (West Bay, 4.5 mg m^{-2} d^{-1}); and Green Pond, also a drowned river valley estuary on Vineyard Sound which shows rates in the upper and lower basins of 12.9 and 30.5 mg m^{-2} d^{-1}, respectively. In addition estuaries not associated with Nantucket/Vineyard Sound also have rates consistent with the basin type of Lake Tashmoo, e.g. The River within Pleasant Bay supporting rates of 12.0 - 34.2 mg N m^{-2} d^{-1} and Phinneys Harbor on Buzzards Bay, 2.9 - 9.4 mg m^{-2} d^{-1}.

Net nitrogen release rates for use in the water quality modeling effort for the main basins of the Lake Tashmoo system (Section VI) are presented in Table IV-5. There was a clear spatial pattern of sediment nitrogen flux, with greater nitrogen release rates from sediments in the upper versus lower basin. The upper reach (South Basin) receives most of the watershed nitrogen discharge and has the highest water column nitrogen and highest sediment release of nitrogen. The lower reaches of the lower basin supported a slightly lower nitrogen release. Overall, the sediments within the Lake Tashmoo Estuary showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters. The nitrogen flux rates are consistent with the level of nitrogen loading to this system and its relatively high flushing rate.

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

	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			
Location	**Mean**	**S.E.**	**# sites**	**TMO- Station ID ***
Lake Tashmoo Estuarine System				
Upper-Mid Pond – (south)	17.6	17.5	6	1,2,3,4,5,6
Lower Pond – (north)	12.8	9.4	10	7,8,9,10/11,12-16

* Station numbers refer to Figure IV-7.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes the field data collection effort and the development of the hydrodynamic model for the Lake Tashmoo estuary system (Figure V-1). For this system, the final calibrated model offers an understanding of water movement through the estuary and provides the first step towards evaluating water quality, as well as a tool for later determining nitrogen loading “thresholds”. Tidal flushing information is utilized as the basis for a quantitative evaluation of water quality. Nutrient loading data combined with measured environmental parameters within the various sub-embayments become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing estuarine water quality, as well as determining the likely positive impacts of implementing various alternatives for improving overall estuarine health, enabling the bordering community to understand how pollutant loadings into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

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

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

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

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

Located on the northern shore of Martha's Vineyard in the town of Tisbury, the Lake Tashmoo estuary system (Figure V-1) is a tidally dominated embayment open to Vineyard Sound through a set of jetties at its northern extent. The total length (north-south) of the estuarine reach of the basin is approximately 1.5 miles (7,920 ft.), by a width of 0.8 miles (4,224 ft.) at its widest point (across the northern extent), and has a mean depth of -4.1 ft. NGVD. The northern quarter of the basin is relatively shallow with greatest depths in the system existing in the southern three quarters of the Pond. Average depths in the deeper southern half of the basin are -6.2 ft. NGVD, with maximum depth of -14.9 ft. NGVD.

Since the water elevation difference between Vineyard Sound and the inland reaches of Lake Tashmoo is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) along the length of the Pond is negligible, indicating a system that is flushed efficiently. Any issues with water quality, therefore, would likely be due to other factors including nutrient loading conditions from the system's watersheds, and the small tide range in Vineyard Sound.

Circulation in the Lake Tashmoo system was simulated using the RMA-2 numerical hydrodynamic model. To calibrate the model, field measurements of water elevations and bathymetry were required. Tide data were acquired within Vineyard Sound at a gage station located just offshore the entrance to Lake Tashmoo and a station located within Lake Tashmoo south of Brown Point. All temperature-depth recorders (TDRs or tide gages) were installed for a 34-day period to measure tidal variations through two fortnightly neap-spring cycles. In this manner, attenuation of the tidal signal as it propagates through the embayment was evaluated accurately.

V.2 FIELD DATA COLLECTION AND ANALYSIS

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

- To accurately define the system geometry and boundary conditions for the numerical model

- To provide 'real' observations of hydrodynamic behavior to calibrate and verify the model results

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

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

To complete the field data collection effort for this study, and to provide model verification data, a survey of velocities was completed at the inlet to Lake Tashmoo. The survey was performed to determine flow rates at the inlet at discreet times during the course of a full tide cycle. Velocity surveying was completed using Acoustic Doppler Current Profiling (ADCP).

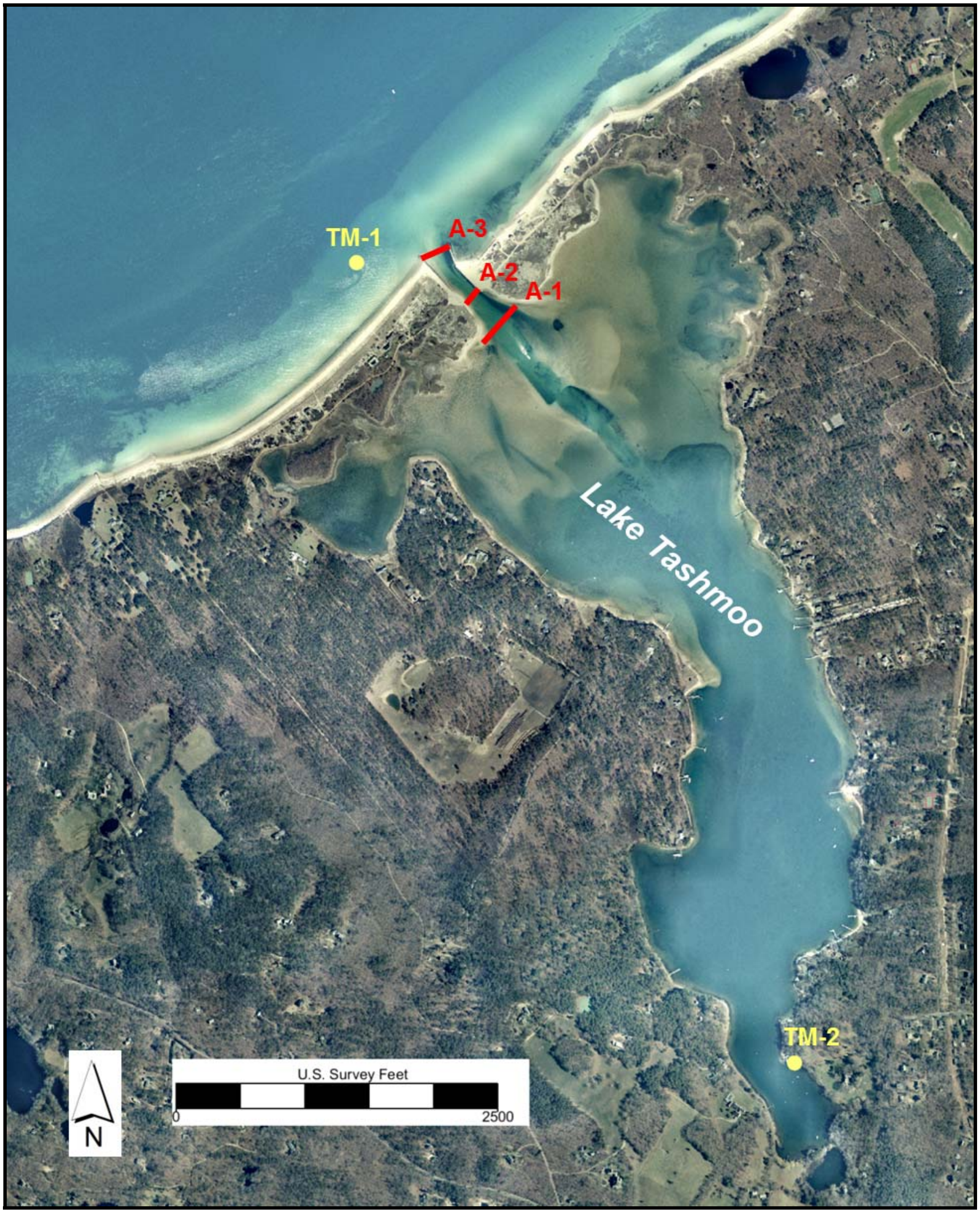

Figure V-2. Map of the study region identifying locations of the tide gauges used to measure water level variations throughout the system and locations of the ADCP transects (A 1-3). Two gauges were deployed for the 34-day period between July 19 and August 23, 2004. Each yellow dot represents the approximate locations of the tide gauges: (TM-1) Vineyard Sound (Offshore) and (TM-2) in Lake Tashmoo south of Brown Point. Each red line represents the location of an APCD transect that was run hourly on August 11, 2004: (A-1) inside the inlet to Lake Tashmoo, (A-2) inside the inlet to Lake Tashmoo, and (A-3) located outside the mouth of the inlet to Lake Tashmoo

V.2.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Lake Tashmoo system was assembled from two main sources: (1) historical data from previous National Ocean Service (NOS) surveys, and (2) a recent hydrographic survey performed specifically for this study. Historical NOS survey data, where available, were used for areas in Vineyard Sound that were not covered by the more recent survey.

The hydrographic survey of August, 2004 (CRE, 2004) was designed to cover the entire basin of Lake Tashmoo. Survey transects were densest in the vicinity of the inlet, where the greatest variability in bottom bathymetry was expected. Bathymetry in the inlet is important from the standpoint that it has the most influence on tidal circulation in and out of the pond. The survey was conducted from an outboard motorboat with an installed high precision fathometer (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide position measurements accurate to approximately 1-3 feet. Digital data output from both the echo sounder fathometer and GPS were logged to a laptop computer which integrated the data to produce a single data set consisting of water depth as a function of geographic position (latitude/longitude).

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to the NGVD 1927 vertical datum. Once rectified, the finished processed data were archived as ‘xyz’ files containing x-y horizontal position (in Massachusetts State Plan 1983 coordinates) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The final processed bathymetric data from the survey are presented in Figure V-3.

V.2.2 Tide Data Collection and Analysis

Changes in water surface elevation were measured using internal recording tide gauges. These tide gauges were installed on fixed platforms (such as pier pilings or screw anchors) to record changes in water pressure over time. Variations in the water surface can be due to tides, wind set-up, or other low frequency oscillations of the sea surface. The tide gauges were installed in 2 locations in Lake Tashmoo (Figure V-2) on July 19, 2004 and recovered on August 23, 2004. Data records span at least 29 days to yield an adequate time period for resolving the primary tidal constituents.

The tide records from Lake Tashmoo were corrected for atmospheric pressure variations and then rectified to the NGVD 27 vertical datum. Atmospheric pressure data, available in one-hour intervals from the NDBC Buzzards Bay C-MAN platform, were used to pressure correct the raw tide data. Final processed tide data from stations used for this study are presented in Figure V-4, for the complete 34-day period of the TDR deployment.

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

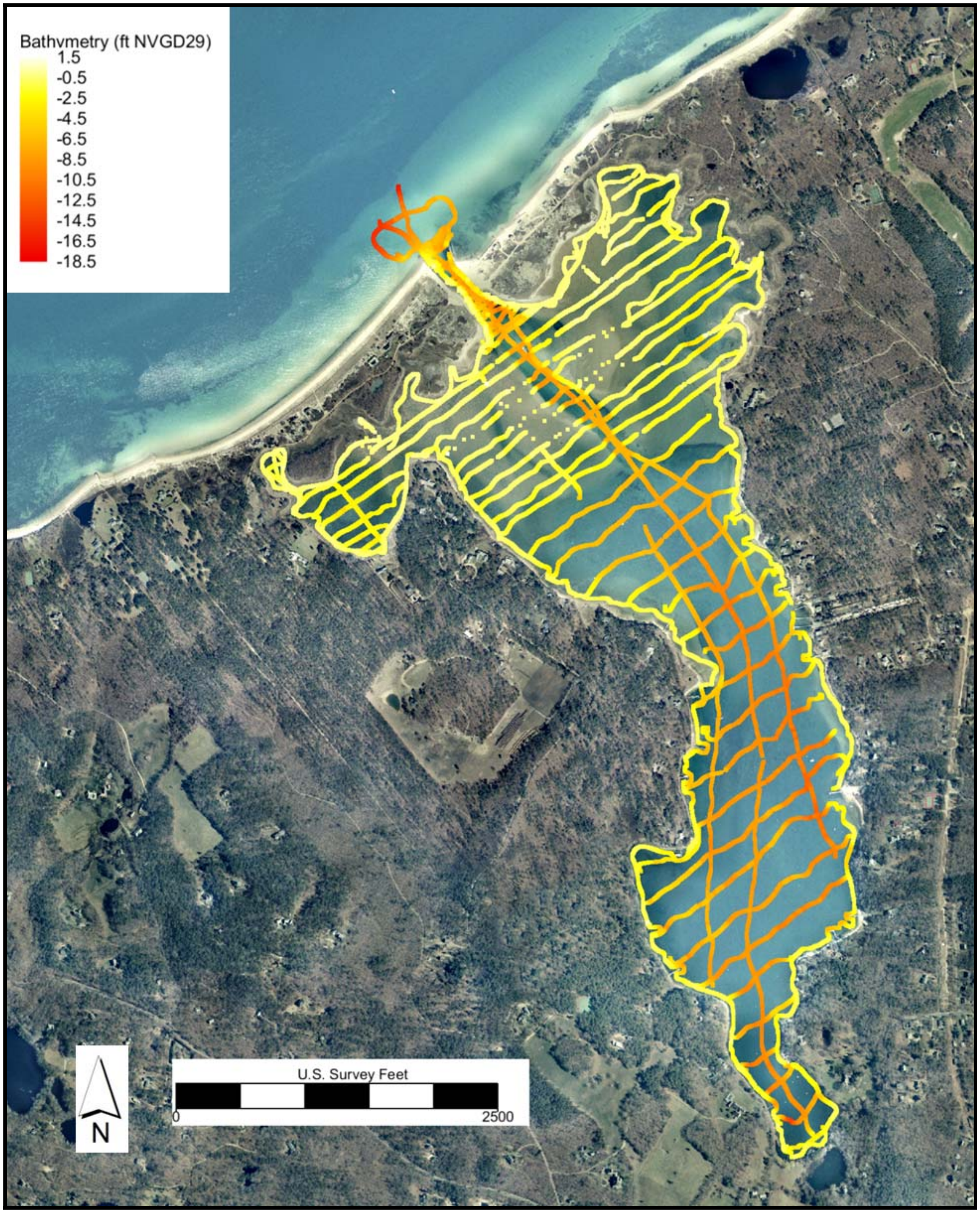

Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

The loss of amplitude together with increasing phase delay as distance from the inlet grows is described as tidal attenuation. Tide attenuation can be a useful indicator of flushing efficiency in an estuary. Attenuation of the tidal signal is caused by the geomorphology of the nearshore region, where channel restrictions (e.g., bridge abutments) and also the depth of an estuary are the primary factors which influence tidal damping in estuaries. For Lake Tashmoo, a visual comparison in Figure V-5 between tide elevations demonstrates how little change there is between the tide range and timing from Vineyard Sound to the farthest inland reach of the Lake Tashmoo. This provides an initial indication that flushing conditions in the estuary are ideal, with minimal loss of tidal energy along the length of the system.

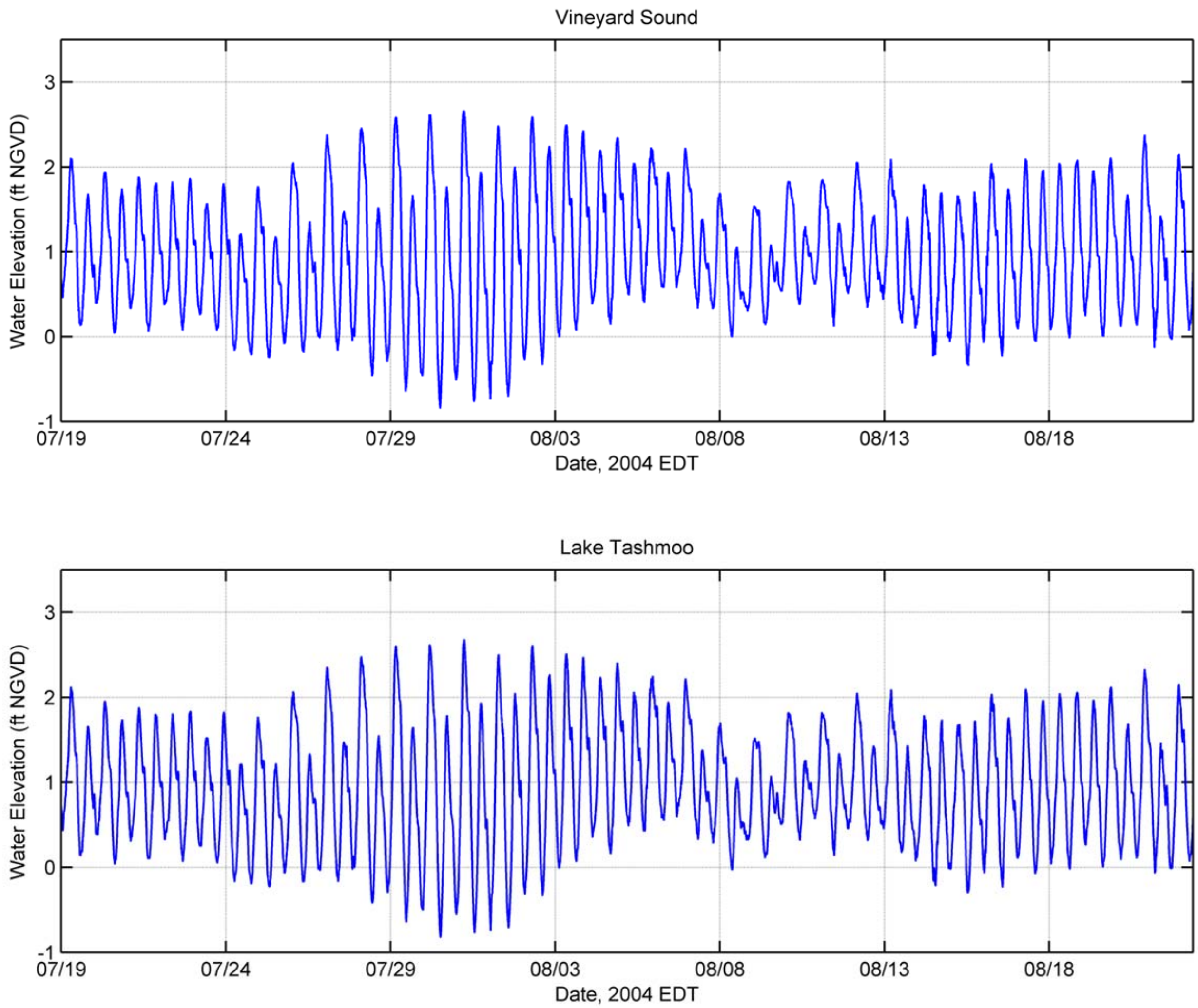

Figure V-4. Variations in water elevation measured in Vineyard Sound and Lake Tashmoo, from July 19 – August 23, 2004.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 34-day records. These datums are presented in Table V-1. The Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW. The tides in Vineyard Sound are semi-diurnal, meaning that there are typically two tide cycles in a day. There is usually a small variation in the level of the two daily tides. This variation can be seen in the differences between the MHHW and MHW, as well as the MLLW and MLW levels. The computed datums for Lake Tashmoo and Vineyard Sound compare well to similar datums computed for Lagoon Pond and Vineyard Haven Harbor using a 32-day record from May/June 2004 (MTL 0.9 ft., MHW 1.7 ft, MLW 0.0 ft NGVD).

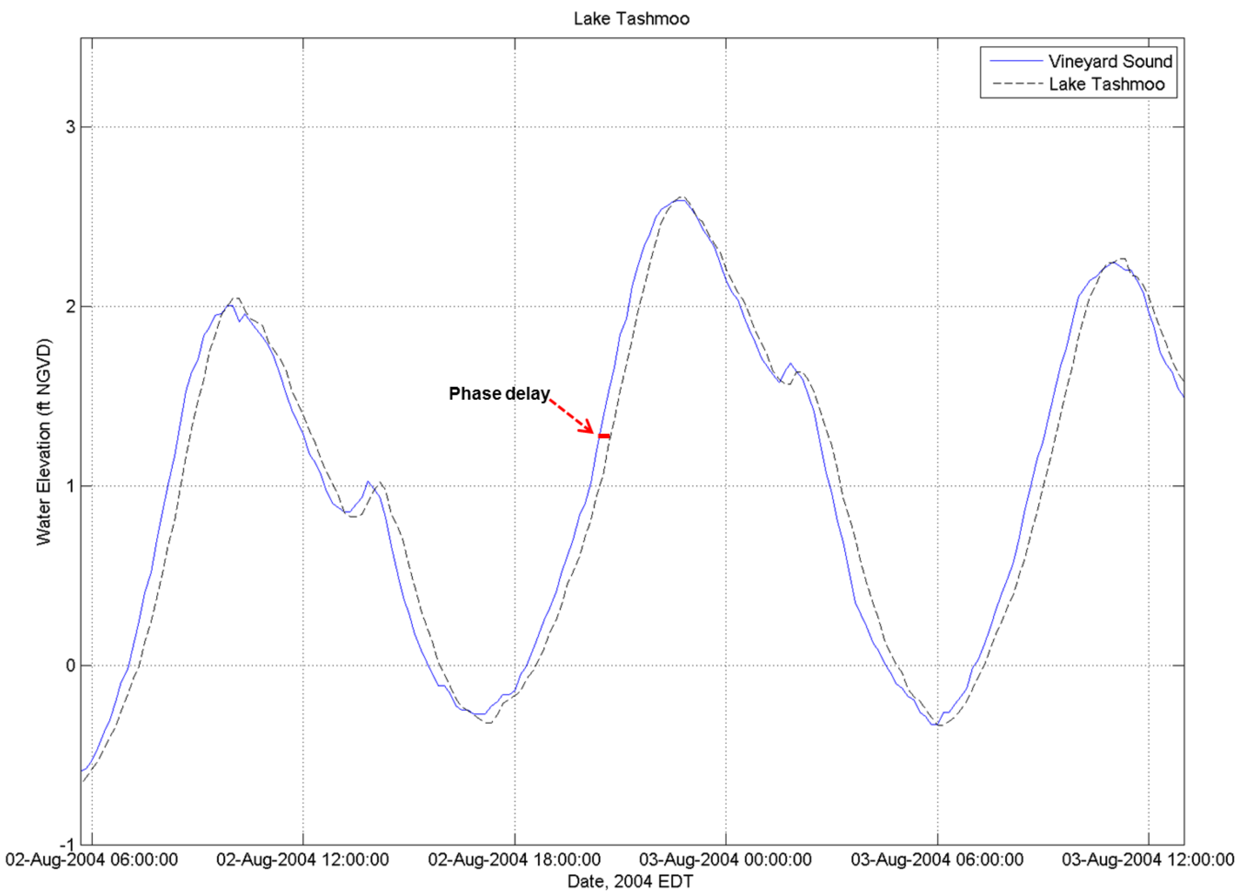

Figure V-5 Plot showing two tide cycles tides in the Lake Tashmoo system. Demonstrated in this plot is the phase delay effect caused by the propagation of the tide through the estuary.

Table V-1. Tide datums computed from records collected in the Lake Tashmoo system July 19 to August 23, 2004. Datum elevations are given relative to NGVD 29 in feet.

Tide Datum	Vineyard Sound	Lake Tashmoo
Maximum Tide	2.66	2.68
MHHW	2.12	2.11
MHW	1.89	1.90
MTL	0.96	0.96
MLW	0.02	0.02
MLLW	-0.08	-0.08
Minimum Tide	-0.85	-0.82

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

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

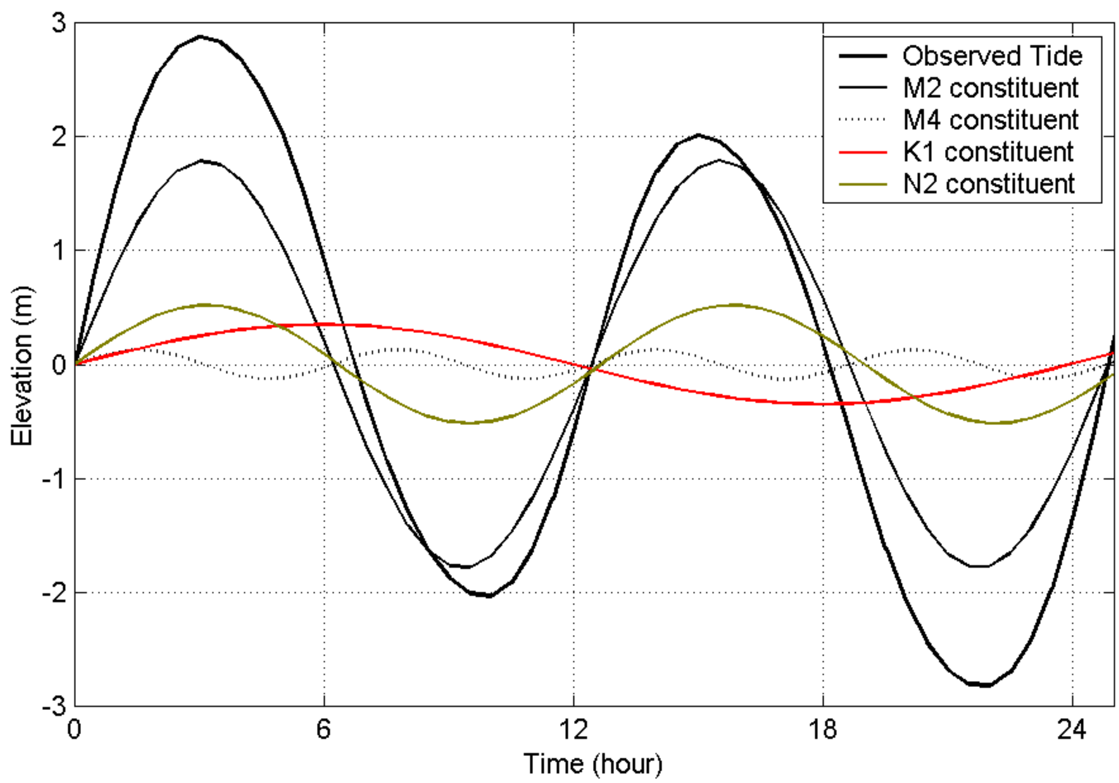

Figure V-6. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-2 presents the amplitudes of eight significant tidal constituents. The M_2, or the familiar twice-a-day lunar semi-diurnal, tide is the strongest contributor to the signal with an amplitude of 0.82 feet in Vineyard Sound. The range of the M_2 tide is twice the amplitude, or about 1.64 feet. The diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar), possess amplitudes of approximately 0.26 and 0.22 feet respectively. Other semi-diurnal tides, the S2 (12.00 hour period) and N2 (12.66-hour period) tides, also contribute to the total tide signal, with amplitudes of 0.17 feet and 0.28 feet, respectively. The M4 and M6 tides are higher frequency harmonics of the M2 lunar tide (exactly half the period of the M2 for the M4, and one third of the M2 period for the M6), results from frictional attenuation of the M2 tide in shallow water. Typically the M4 represents a small fraction of the total tide amplitude. However, in Vineyard Sound, the M4 and M6 amplitudes are large compared to the M2 (i.e., 17% and 9%

of the Vineyard Sound M2 amplitude, respectively), and as a result, they have more influence on the shape of the tide signal than is observed in most other parts of the world's oceans.

Table V-2. Tidal Constituents for stations in the Lake Tashmoo System, from data collected July 19 to August 23, 2004.

	AMPLITUDE (feet)							
Tidal Constituents	**M2**	**M4**	**M6**	**S2**	**N2**	**K1**	**O1**	**MSF**
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Vineyard Sound	0.82	0.14	0.07	0.17	0.28	0.26	0.22	0.09
Lake Tashmoo	0.81	0.15	0.08	0.17	0.27	0.25	0.22	0.10

Table V-3 presents the phase delay (in other words, the travel time required for the tidal wave to propagate throughout the system) of the M2 tide from Vineyard Sound to the southern reaches of Lake Tashmoo. However, the degree of attenuation is not significant relative to the hydraulic efficiency of the system because the effects of attenuation are observed only in the phase delay across the system, and not as a reduction in the amplitude of the tide (or tidal constituents).

Table V-3. M2 Tidal Attenuation, Lake Tashmoo System, July – August 2004 (Delay in minutes relative to Vineyard Sound).

Location	Delay (minutes)
Lake Tashmoo	14.27

The tide data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. Non-tidal processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow. The results of an analysis to determine the energy distribution (or variance) of the measured water elevation records for the gauge records in Lake Tashmoo compared to the energy content the astronomical tidal signal (re-created by summing the contributions from the 21 constituents determined by the harmonic analysis) is presented in Table V-4. Subtracting the tidal signal from the measured elevation time series yielded the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes are relative to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from Vineyard Sound, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

Table V-4 shows that the percentage contribution of tidal energy was essentially equal in all parts of the system, indicating that local effects due to winds and other non-tidal processes are minimal throughout the systems. The analysis also shows that tides are responsible for approximately 94% of the water level changes in Lake Tashmoo. The remaining 6% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of Lake Tashmoo and Vineyard Sound. The total energy content of the tide signal from each gauging station does not change significantly, nor does the relative contribution of tidal vs. non-tidal forces along the estuary basin. This is further indication that tide attenuation across the inlet and through the system is negligible. It is also an indication that the source of the non-tidal component of the tide signal is generated completely offshore, with no additional non-tidal energy input inside the pond (e.g., from wind set-up of the pond surface).

Table V-4. Percentages of Tidal versus Non-Tidal Energy, Parker River, 2004

	Total Variance	Total	Tidal	Non-tidal
Unit	(ft^2)	(%)	(%)	(%)
Vineyard Sound	0.49	100	93.7	6.3
Lake Tashmoo	0.47	100	93.8	6.2

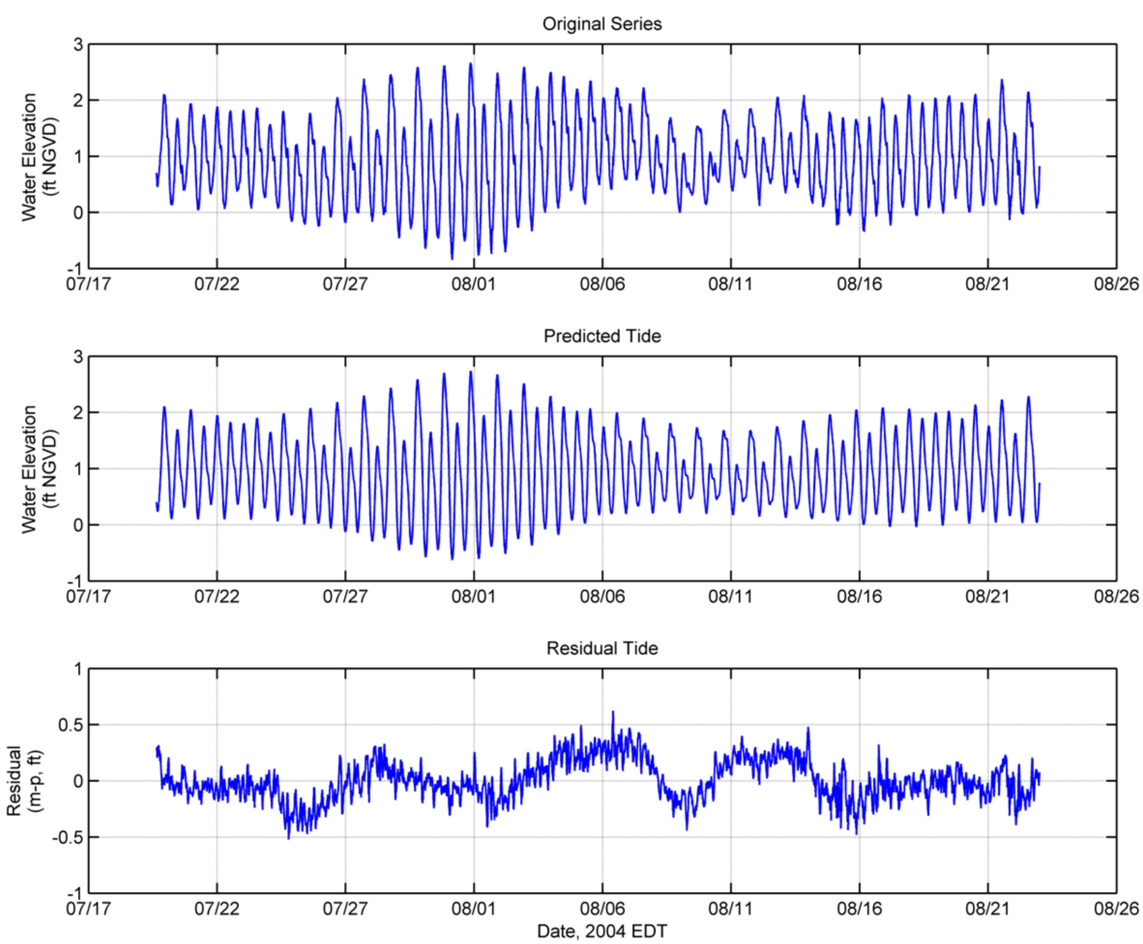

Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured in Vineyard Sound (TM-1).

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

V.2.3 ADCP Data Analysis

The current velocity measurements in the inlet to Lake Tashmoo were collected using an Acoustic Doppler Current Profiler (ADCP) mounted aboard a small survey vessel. The boat repeatedly navigated three pre-defined transect lines through the area, approximately every 60 minutes, with the ADCP continuously collecting current profiles. This pattern was repeated for approximately 12.5-hours to ensure measurements over the entire tidal cycle. The results of the data collection effort are high-resolution observations of the spatial and temporal variations in tidal current patterns throughout the survey area.

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

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

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

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

Current measurements were collected by the ADCP as the vessel repeatedly navigated the three pre-defined transect lines in Lake Tashmoo (Figure V-2). The line-cycles were repeated every hour throughout the survey. The first cycle was begun at 06:14 hours (Eastern Daylight Time, EDT) and the final cycle was completed at 18:58 hours (EDT), for a survey duration of approximately 12.5 hours on August 11, 2004 that captured the range of current velocities from high to low tide.

V.3 HYDRODYNAMIC MODELING

The focus of the MEP hydrodynamic effort was the development of a numerical model capable of accurately simulating hydrodynamic circulation within the Lake Tashmoo estuary system. Once calibrated, the model was used to calculate water volumes for selected sub-embayments (e.g., Rhoda Pond, Drew Cove, and the upper estuarine reach of Lake Tashmoo) as well as determine the volumes of water exchanged during each tidal cycle. These parameters are used to calculate system residence times, or flushing rates. The ultimate utility of the hydrodynamic model is to supply required input data for the water quality modeling effort described in Chapter VI.

V.3.1 Model Theory

This study of Lake Tashmoo utilized a state-of-the-art computer model to evaluate tidal circulation and flushing. 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 for estuary systems in southeastern Massachusetts, including systems in across Cape Cod (e.g. Chatham, Falmouth's 'finger' ponds, Popponesset Bay) as well as the islands (e.g. Nantucket).

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). SMS is a front- and back-end software package that allows the user to easily modify model parameters (such as geometry, element coefficients, and boundary conditions), as well as view the model results and download specific data types. While the RMA model is essentially used without cost or constraint, the SMS software package requires site licensing for use.

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

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

V.3.2.1 Grid Generation

The grid generation process for the model was assisted through the use of the SMS package. The digital shoreline and bathymetry data were imported to SMS and a finite element grid with 1805 elements and 5669 nodes was generated to represent the estuary (Figure V-8). All regions in the system were represented by two-dimensional (depth-averaged) elements. The finite element grid for the system provided the detail necessary to accurately evaluate the variation in hydrodynamic properties within the estuary. Fine scale resolution was required to simulate the channel constrictions (e.g., at Lake Tashmoo's inlet) that significantly impact the estuarine hydrodynamics. The completed grid is made up of quadrilateral and triangular two-dimensional elements. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the recent field surveys and the NOS data archive. The final interpolated grid bathymetry is shown in Figure V-9. The model computed water elevation and velocity at each node in the model domain.

Grid resolution is governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each region. Smaller cross channel node spacing in the river channels was designed to provide a more detailed analysis in these regions of rapidly varying velocities and bathymetry. Widely spaced nodes were utilized in areas where velocity gradients were likely to be less acute; for example, on marsh plains and in broad, deep channel sections in the model domain. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

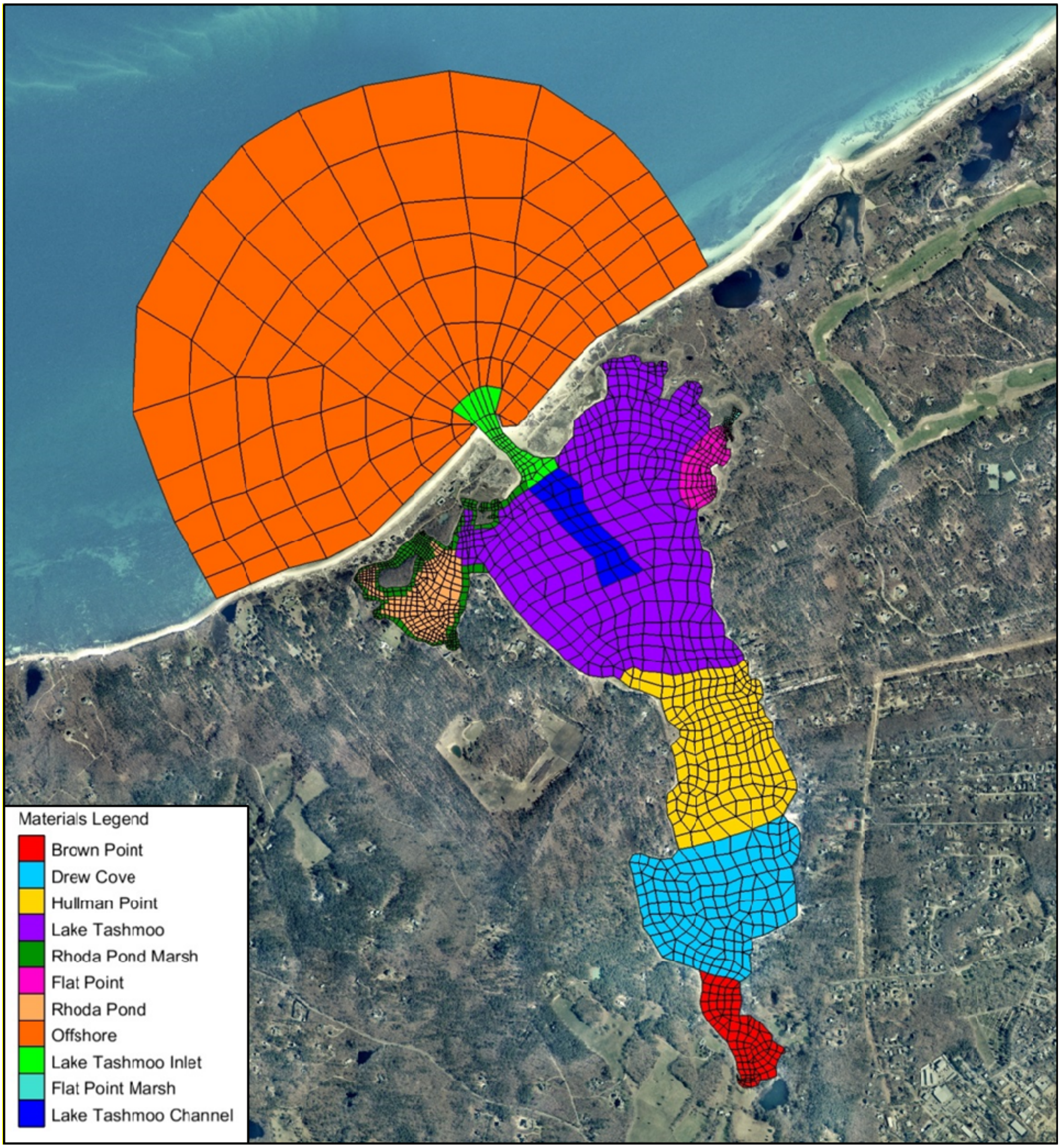

Figure V-8. The model finite element mesh developed for Lake Tashmoo estuary system. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained in Vineyard Sound.

V.3.2.2 Boundary Condition Specification

Three types of boundary conditions were employed for the RMA-2 model: 1) "slip" boundaries, 2) freshwater inflow, and 3) tidal elevation boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained to shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. A freshwater inflow boundary condition was specified at the fish ladder from Upper Lake Tashmoo.

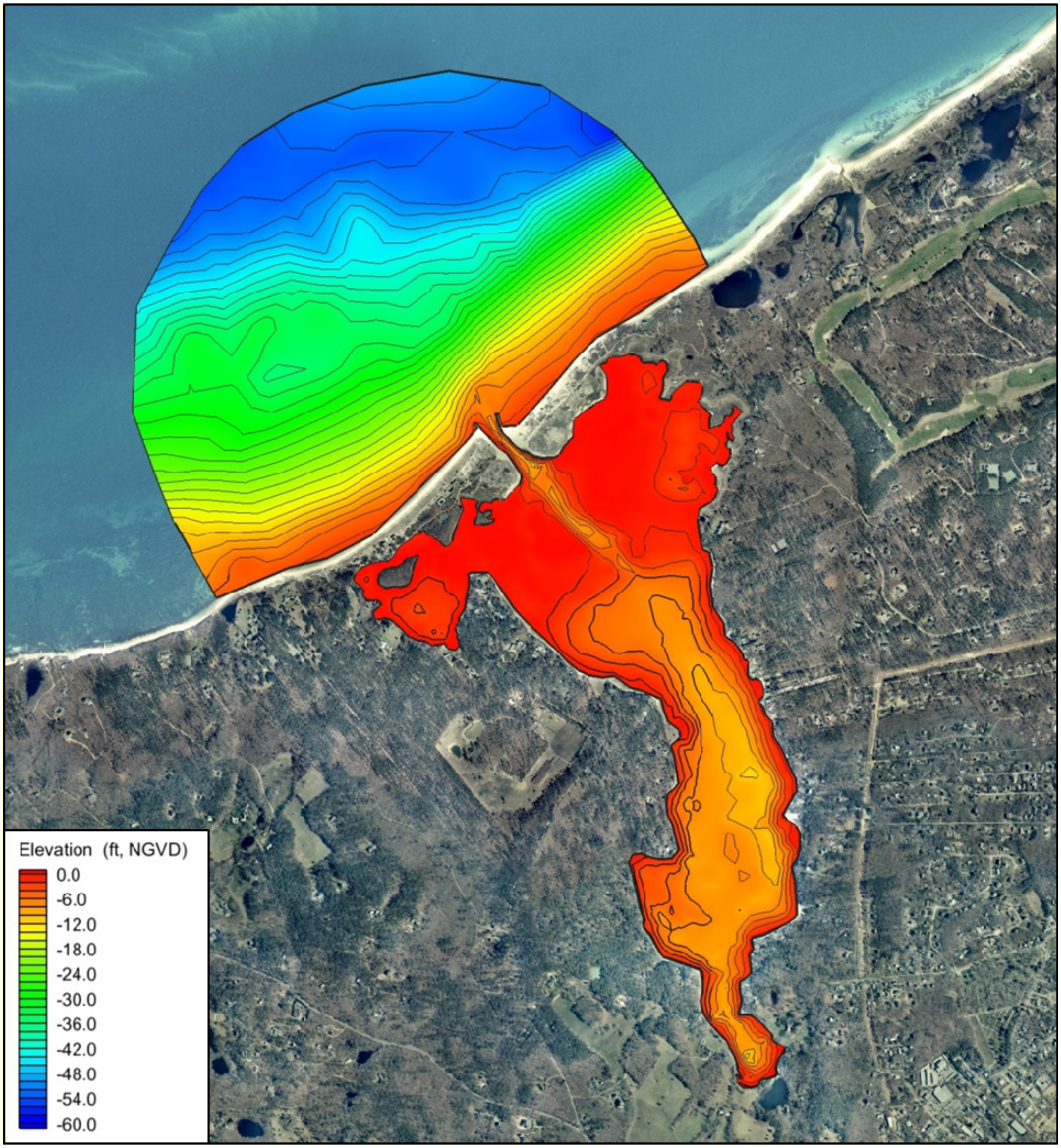

Figure V-9. Depth contours of the completed Lake Tashmoo finite element mesh.

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

V.3.3 Calibration

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

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

The calibration was performed for an approximate eight-day period, beginning 0340 hours EDT July 26, 2004 and ending 0340 EDT August 3, 2004. This time period included a 12-hour model spin-up period and a 15-tide cycle period used for calibration. This representative time period was selected because it included tidal conditions where the wind-induced portion of the signals (i.e. the residual) was minimal, hence more typical of tidal circulation within the estuary. The selected time period also spanned the transition from neap (bi-monthly minimum) to spring (bi-monthly maximum) tide ranges, which is representative of average tidal conditions in the embayment system. Throughout the selected 8 day period, the tide ranged approximately 3.5 feet from minimum low to maximum high tides. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. Modeled tides were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.3.3.1 Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where water depths can become shallow and velocities relatively high. Friction is a measure of the channel roughness and can cause both significant amplitude attenuation and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient. First, Manning's friction coefficient values of 0.025 were specified for all elements. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels with pools and shoals with higher friction (Henderson, 1966). On the marsh plains of Rhoda Pond and Flat Point, damping of flow velocities typically is controlled more by "form drag" associated with marsh plants than the bottom friction described above. However, simulation of this "form drag" is performed using Manning's coefficients as well, with values ranging from 1.5-to-10 times friction coefficients used in sandy channels. Final calibrated friction coefficients (listed in Table V-5) were largest for marsh plain area, where values were set at 0.035. Small changes in these values did not change the accuracy of the calibration.

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

Embayment	Bottom Friction
Offshore (Vineyard Sound)	0.025
Lake Tashmoo Inlet	0.025
Lake Tashmoo Channel	0.025
Lake Tashmoo	0.025
Rhoda Pond	0.025
Rhoda Pond Marsh	0.035
Flat Point	0.025
Flat Point Marsh	0.035
Hullman Point	0.025
Drew Cove	0.025
Brown Point	0.025

V.3.3.2 Turbulent Exchange Coefficients

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

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

Embayment	D (lb-sec/ft$^{2)}$
Offshore (Vineyard Sound)	50
Lake Tashmoo Inlet	50
Lake Tashmoo Channel	50
Lake Tashmoo	50
Rhoda Pond	50
Rhoda Pond Marsh	100
Flat Point	50
Flat Point Marsh	100
Hullman Point	50
Drew Cove	50
Brown Point	50

V.3.3.3 Wetting and Drying/Marsh Porosity Processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain included in the model as part of Rhoda Pond and Flat Point in the Lake Tashmoo 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 initially rises within the channels and creeks until water surface elevation reaches the marsh plain. At this point the water level remains nearly constant as water 'fans' out over the marsh surface. The rapid flooding of the marsh surface corresponds to a flattening out of the tide curve approaching high water. Marsh porosity is a feature of the RMA-2 model that permits the modeling of hydrodynamics in marshes. This model feature essentially simulates the store-and-release capability of the marsh plain by allowing grid elements to transition gradually between wet and dry states. This technique allows RMA-2 to change the ability of an element to hold water, like squeezing a sponge. The marsh porosity feature of RMA-2 is typically utilized in estuarine systems where the marsh plain has a significant impact on the hydrodynamics of a system.

V.3.3.4 Comparison of Modeled Tides and Measured Tide Data

Several calibration model runs were performed to determine how changes to various parameters (e.g. friction and turbulent exchange coefficients) affected the model results. These trial runs achieved excellent agreement between the model simulations and the field data. Comparison plots of modeled versus measured water levels at the two gauge locations is presented in Figures V-10 through V-11. At all gauging stations RMS errors were less than 0.04 ft (<0.5 inches) and computed R^2 correlation was better than 0.99. Errors between the model and observed tide constituents were less than 0.2 inches for all locations, suggesting the model accurately predicts tidal hydrodynamics within Lake Tashmoo. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the calibration time period are shown in Table V-7. The constituent values for the calibration time period differ from those in Tables V-2 because constituents were computed for only 7.5 days, rather than the entire 34-day period represented in Table V-2. Errors associated with tidal constituent height were on the order of hundredths of one foot, which was an order of magnitude better than the accuracy of the tide gage gauges ($\pm$0.12 ft). Time lag errors were less than the time increment resolved by the model and measured tide data (1/6 hours or 10 minutes), indicating good agreement between the model and data.

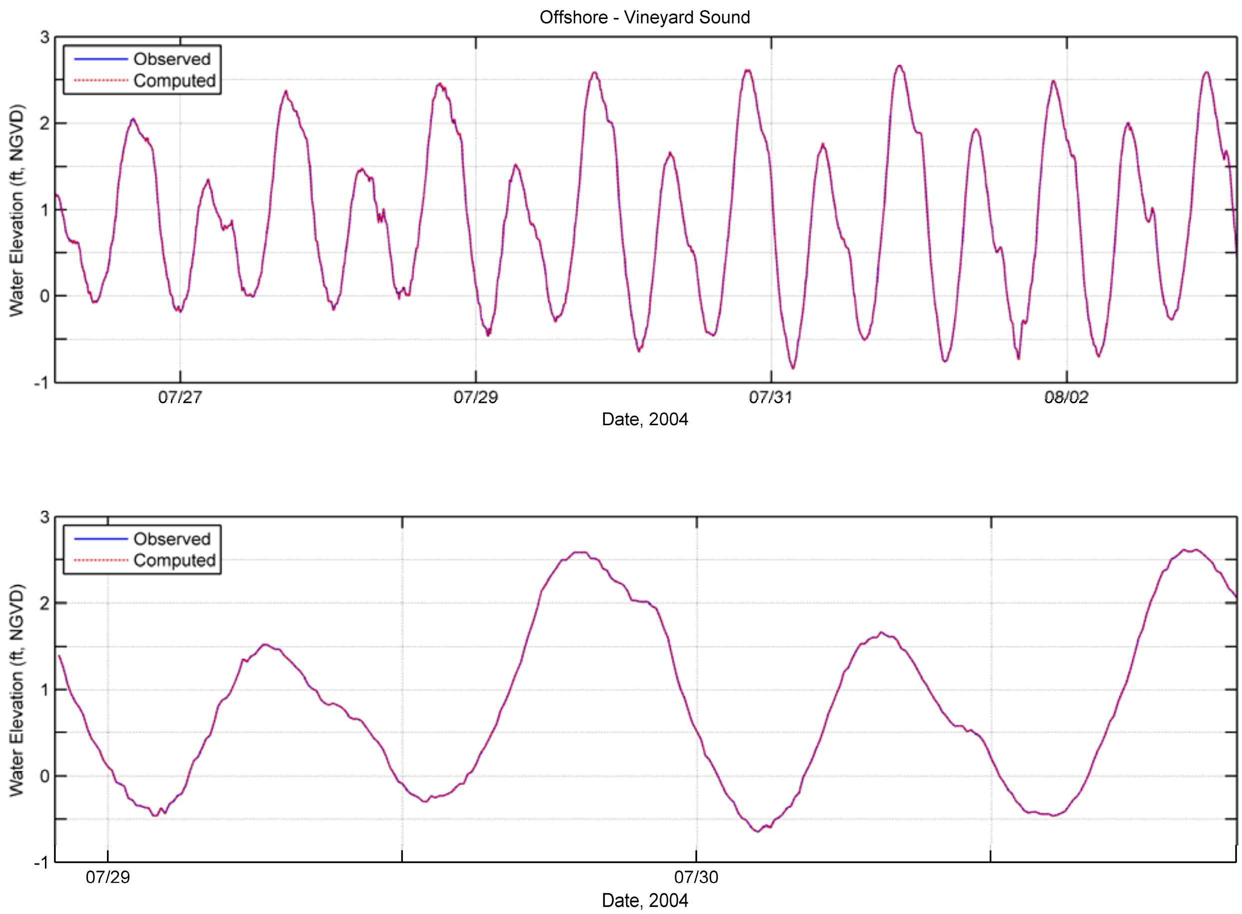

Figure V-10. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period at the offshore gauging station (TM-1). The bottom plot is a 48-hour sub-section of the total modeled time period, shown in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

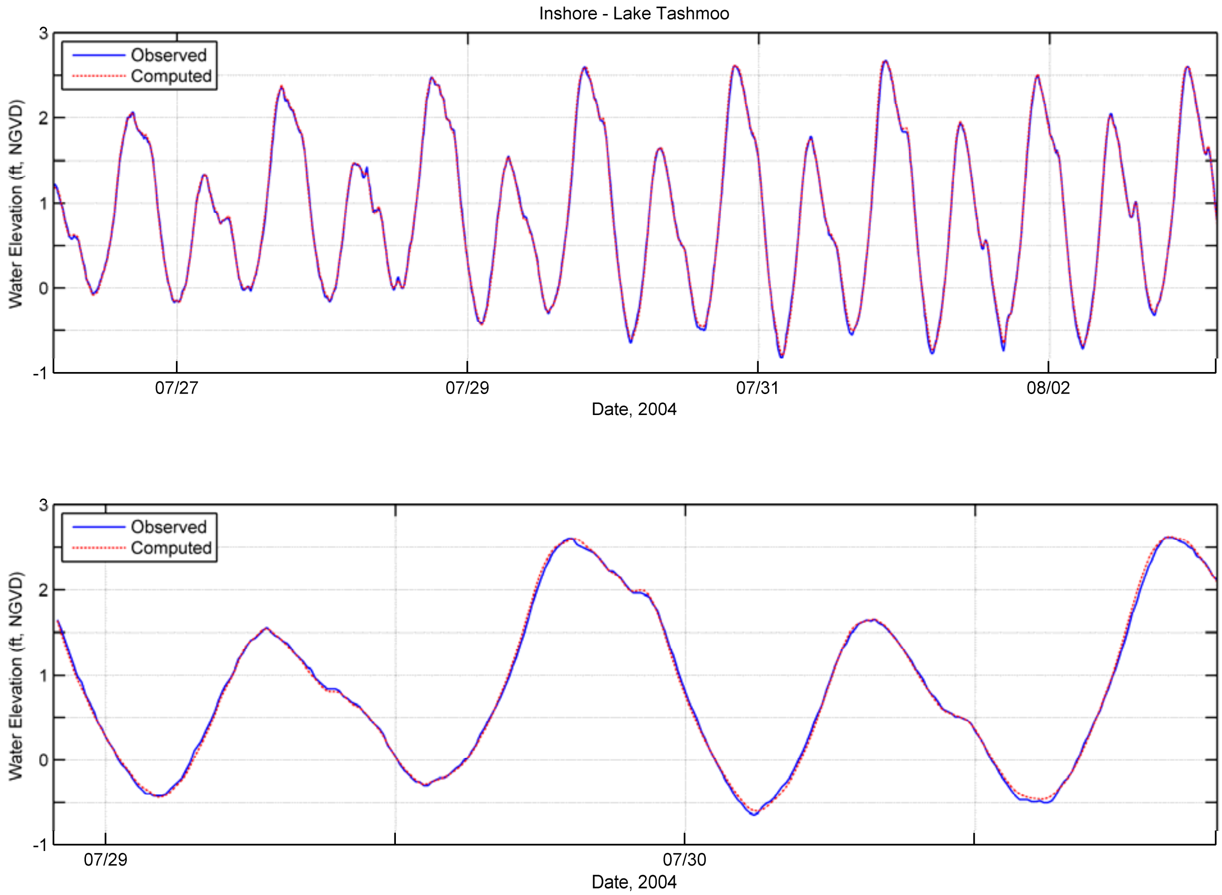

Figure V-11. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period at the Brown Point inlet gauging station (TM-2). The bottom plot is a 48-hour sub-section of the total modeled time period,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

V.3.4 ADCP verification of the Lake Tashmoo system

An additional model verification check was possible by using collected ADCP velocity data to verify the performance of the model in representing the system dynamics. Computed flow rates from the model were compared to flow rates determined using the measured velocity data. The ADCP data survey efforts are described in Section V.2.3. For the model ADCP verification, the Lake Tashmoo model was run for the period covered during the ADCP survey on August 11, 2004. Model flow rates were computed in RMA-2 at continuity lines (channel cross-sections) that correspond to the actual ADCP transects followed in the survey across the Lake inlet.

Data comparisons at the Lake Tashmoo ADCP transects show good agreement with the model predictions, with R^2 correlation coefficients between data and model results ranging from 0.78 to 0.91. A comparison of the measured and modeled volume flow rates at the survey transects are shown in Figures V-12 through V-14. The top plot in the figure shows the flow comparison and the lower plot shows the time series of tide elevations for the same period. Each ADCP point (black circles shown on the plots) is a summation of flow measured along the ADCP transect at a discrete moment in time. The ‘bumps’ and ‘skips’ of the flow rate curve (more evident in the model output) can be attributed mostly to the peculiar nature of the forcing tide in this region, but also to the effects of winds (i.e., atmospheric effects) on the water surface and friction across the seabed periodically retarding or accelerating the flow through the inlets. If water surface elevations changed smoothly as a sinusoid, the volume flow rate would also appear as a smooth curve. However, since the rate at which water surface elevations change does not vary smoothly, the flow rate curve is expected to show short-period fluctuations.

Table V-7. Comparison of Tidal Constituents calibrated RMA2 model versus measured tidal data for the period July 26 to August 3, 2004.

Model Verification Run						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Offshore- Vineyard Sound	1.19	0.18	0.09	0.42	45.67	-26.04
Inshore - Lake Tashmoo	1.17	0.20	0.09	0.43	53.61	-2.61
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Offshore- Vineyard Sound	1.19	0.18	0.09	0.42	45.63	-26.21
Inshore - Lake Tashmoo	1.17	0.19	0.09	0.42	53.86	-6.63
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Offshore- Vineyard Sound	0.00	0.00	0.00	0.00	-0.08	-0.17
Inshore - Lake Tashmoo	0.00	-0.01	0.00	-0.01	0.51	-4.15

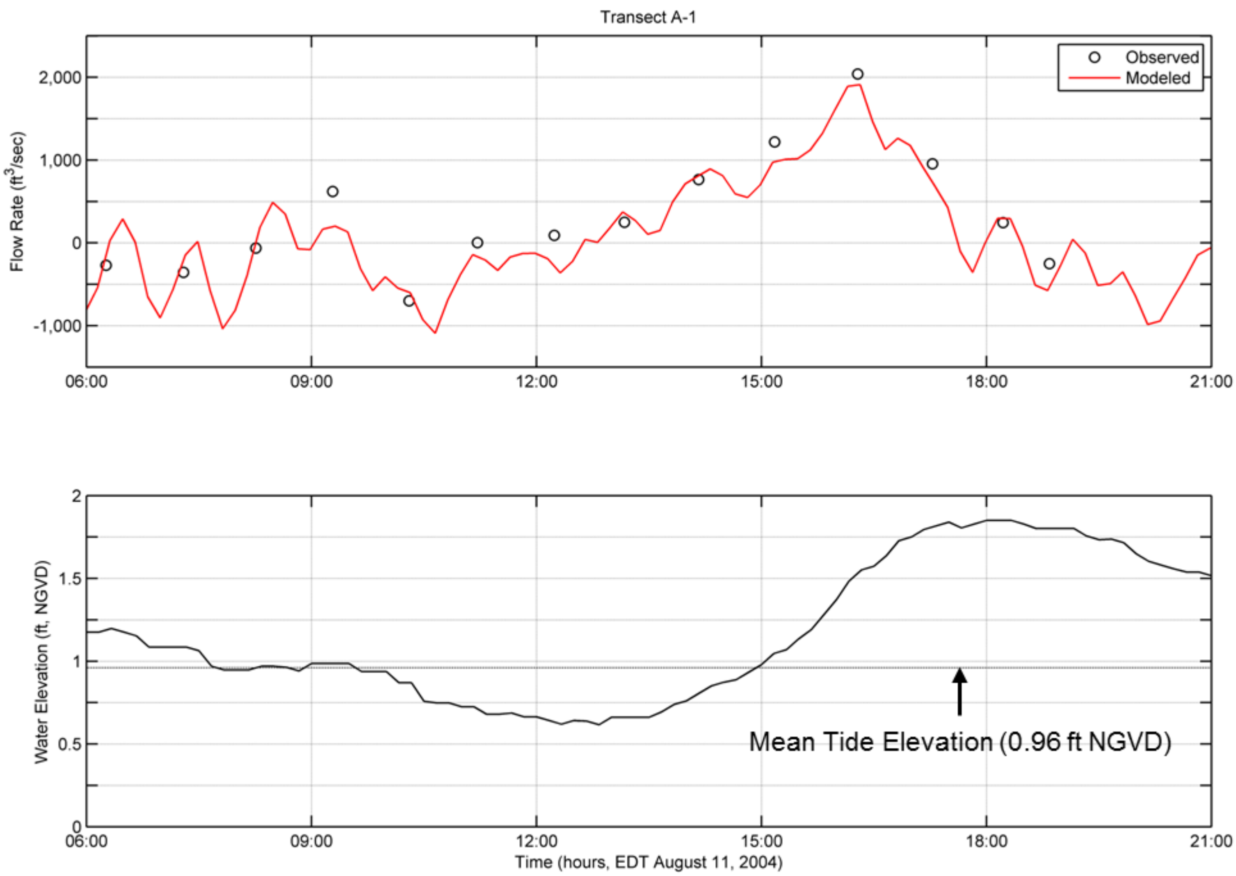

Figure V-12. Comparison of measured volume flow rates versus modeled flow rates (top plot) across Lake Tashmoo inlet (A-1), over a tidal cycle on August 11, 2004 (R^2 = 0.91). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Vineyard Sound.

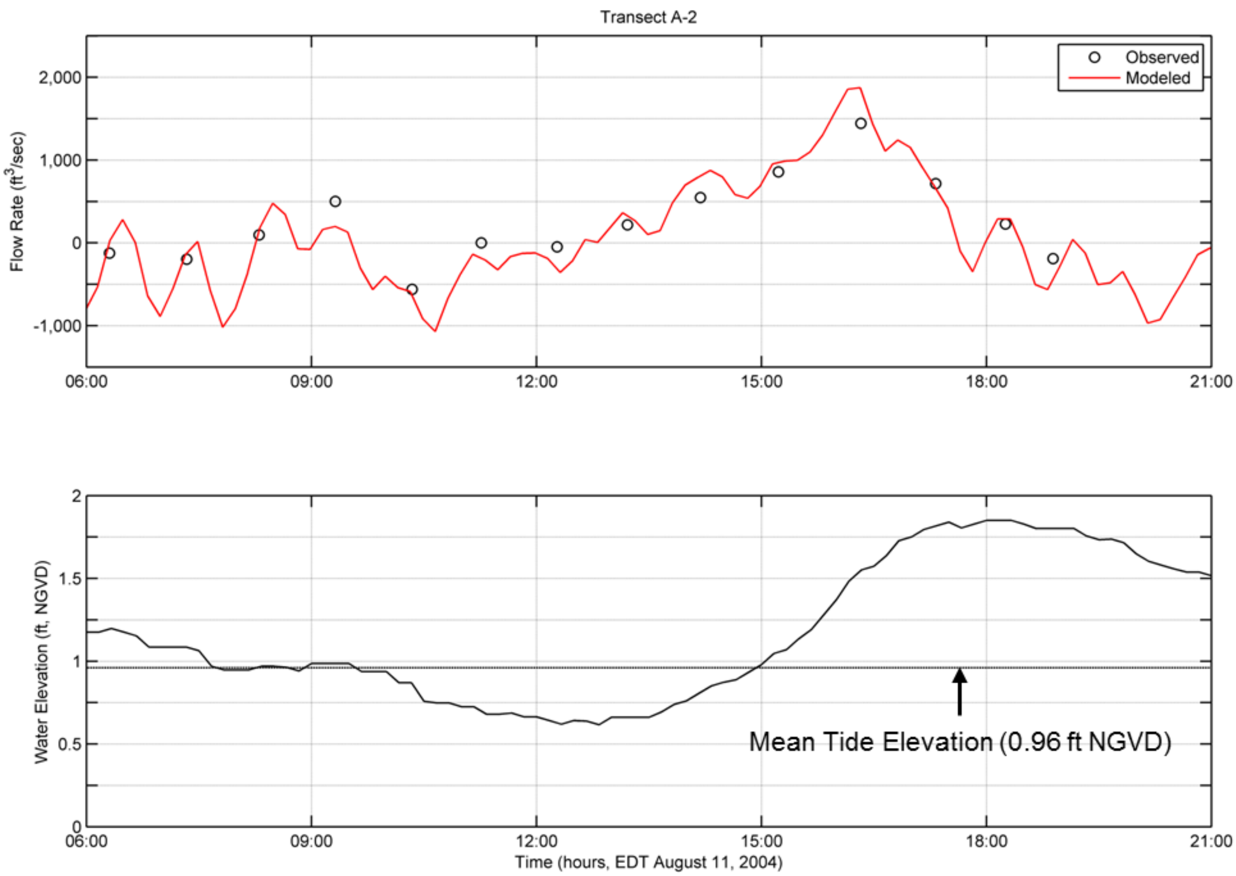

Figure V-13. Comparison of measured volume flow rates versus modeled flow rates (top plot) across Lake Tashmoo inlet (A-2), over a tidal cycle on August 11, 2004 (R^2 = 0.84). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Vineyard Sound.

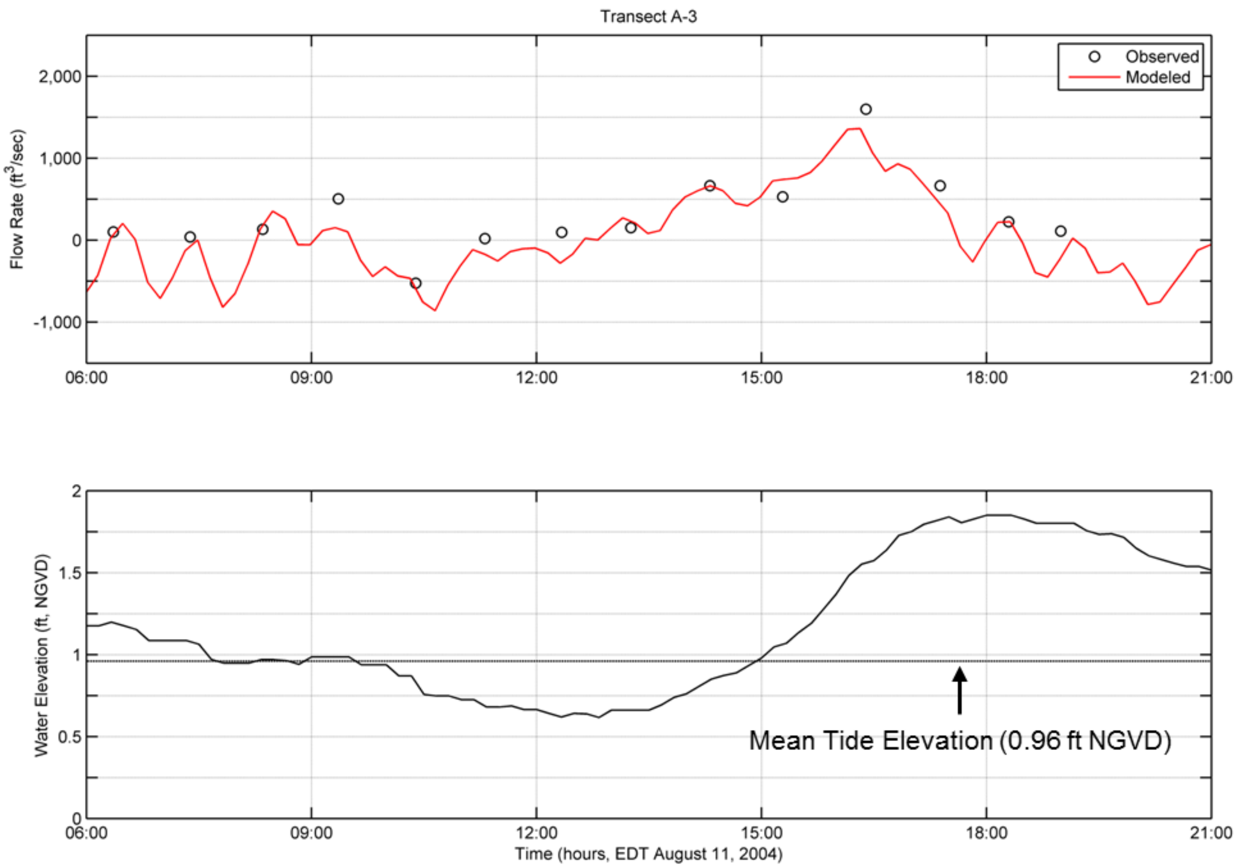

Figure V-14. Comparison of measured volume flow rates versus modeled flow rates (top plot) across Lake Tashmoo inlet (A-3), over a tidal cycle on August 11, 2004 (R^2 = 0.78). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Vineyard Sound.

V.3.5 Model Circulation Characteristics

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

From the model run of Lake Tashmoo, maximum ebb velocities at the inlet are slightly larger than velocities during the flood portion of the tide. Maximum depth-averaged velocities in the model are approximately 3.6 feet/sec for ebbing tides, and 2.7 ft/sec for flooding tides. A close-up of the model output is presented in Figure V-15, which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow, for a single model time-step, at the portion of the tide where maximum ebb velocities occur at the inlet.

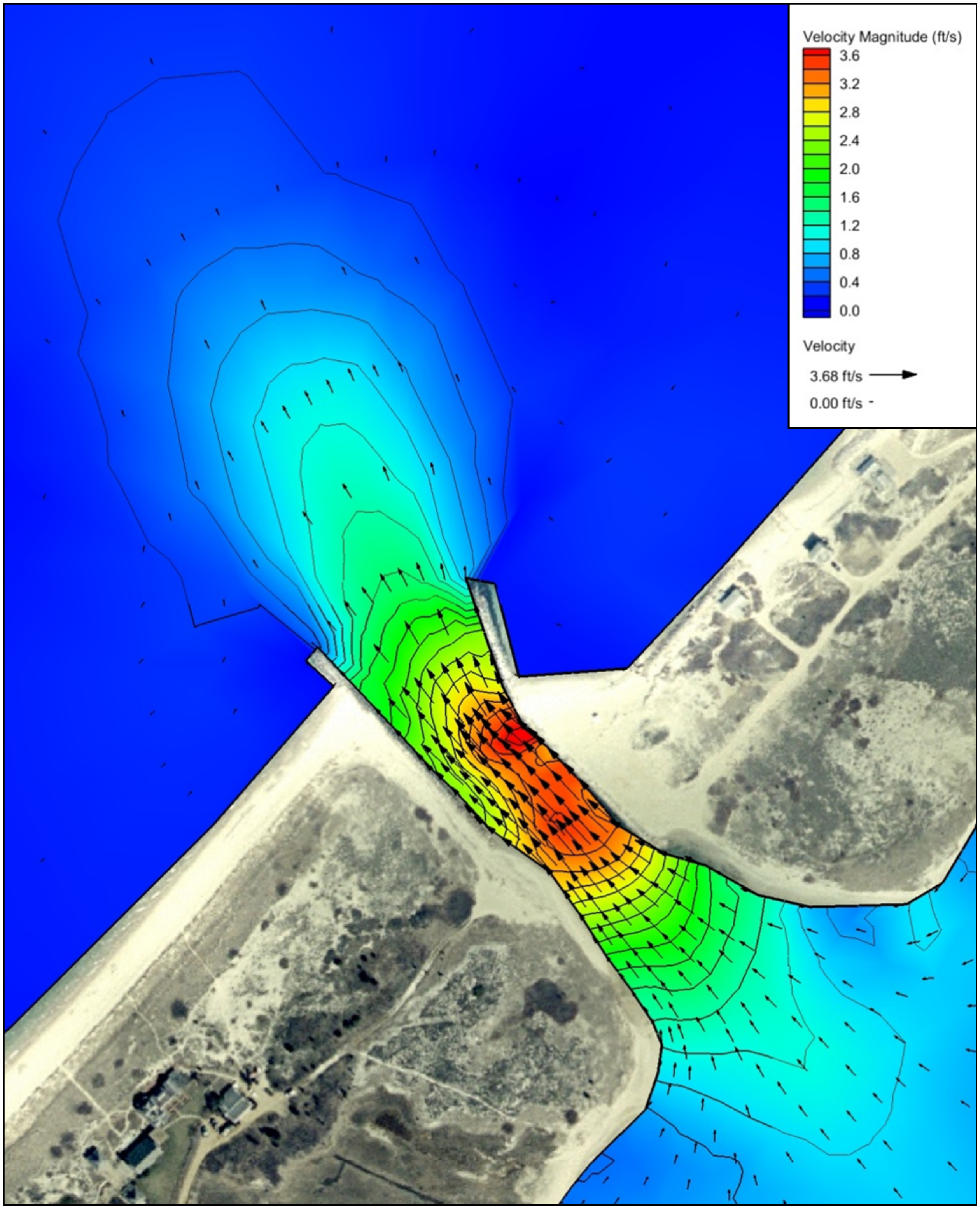

Figure V-15. Example of hydrodynamic model output in Lake Tashmoo's inlet for a single time step where maximum ebb velocities occur for this specific tidal cycle. Color contours indicate flow velocity and vectors indicate the direction and magnitude of flow.

V.5 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through the inlet, the primary mechanism controlling estuarine water quality within Lake Tashmoo is tidal exchange. A rising tide offshore in Vineyard Sound creates a slope in the water surface from the ocean into the modeled system. Consequently, water flows into (floods) the system. Similarly, the estuary drains into the open waters of the Sound on an ebbing tide. This exchange of water between the estuary system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to quantitatively evaluate tidal flushing of each portion of the 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 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 the head of Lake Tashmoo as an example, the system residence time is the average time required for water to migrate from the head of Lake Tashmoo, through the lower portions of the Pond, and finally into Vineyard Sound, where as the local residence time is the average time required for water to migrate from the head of the pond to just the mid portion of the Pond (not all the way to the inlet and out of the system). Local residence times for each sub-embayment are computed as:

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

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

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

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

The volume of the each sub-embayment, as well as their respective tidal prisms, were computed as cubic feet (Table V-8). Model divisions used to define the system sub-embayments include: 1) the entire Lake Tashmoo system, 2) Lake Tashmoo including the channel and inlet, 3) Rhoda Pond including the marsh, 4) Flat Point including the marsh, 5) Hullman Point, 6) Drew Cove, 7) Brown Point, and 8) the offshore portion in Vineyard Sound. The model computed total volume of each sub-embayment (using the divisions shown in Figure V-8), at every time step and this output was used to calculate mean sub-embayment volume and average tidal prism. Since the 7.5-day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

Residence times were averaged for the tidal cycles comprising a representative 7.5 day period (15 tide cycles) and are listed in Table V-9. Residence times were computed for the entire estuary, as well as selected sub-embayments within the system. System residence times were only calculated for four of the sub-embayments, Brown Point, Drew Cove, Hullman Point, and Lake Tashmoo because it is believed that these are the only embayments where the water travels through the majority of the system. In addition, local residence times were computed for each sub-embayment to indicate the range of conditions possible for the system. Residence times were calculated as the volume of water (based on mean volumes computed for the calibration 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 whole Lake Tashmoo system has a low residence time (1.1 days) showing that the system has good flushing conditions. This is true of all the local residence times for the system. The system residence time for Brown Point, Drew Cove, and Hullman Point do not provide a good indication of the water quality since the variation in basin volumes from these sub-embayments to the system volume is considerable. The resulting system residence times are longer, especially for Brown Point, which should not be considered accurate characterization of the conditions occurring in these embayments. A more comprehensive examination of nutrient loading is required to provide an accurate characterization (see Chapter VI).

Table V-8. Embayment mean volumes and average tidal prism of the Lake Tashmoo system during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Entire System	65,402,530	30,063,257
Brown Point	3,462,514	1,288,013
Drew Cove	16,458,598	5,153,338
Hullman Point	17,465,467	5,252,933
Lake Tashmoo (including the inlet and channel)	24,733,880	15,198,360
Rhoda Pond (including marsh)	2,414,315	2,383,163
Flat Point (including marsh)	857,897	809,346
Offshore (Vineyard Sound)	709,418,738	52,333,190

Table V-9. Computed System and Local residence times for sub-embayments of the Lake Tashmoo estuary system.

Embayment	System Residence Time (days)	Local Residence Time (days)
Entire System	1.1	1.1
Brown Point	26.4	1.4
Drew Cove	6.6	1.7
Hullman Point	6.5	1.7
Lake Tashmoo (including the inlet and channel)	2.2	0.5
Rhoda Pond (including marsh)	--	0.6
Flat Point (including marsh)	--	0.8
Offshore (Vineyard Sound)	--	7.0

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 Lake Tashmoo estuary system. Possible errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. In this study, the most significant errors associated with the bathymetry data result from the process of interpolating the data to the finite element mesh, which was the basis for all the flushing volumes used in the analysis. In addition, limited topographic measurements were available in some of the smaller sub-embayments of the system.

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

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

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

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the embayments were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated hydrodynamic model representing the transport of water within the Lake Tashmoo system. Files of node locations and node connectivity for the RMA-2V model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic model output used for the water quality model calibration was the 7 day (15 tide cycle) period beginning 0340 hours EDT July 26, 2004. This period is the same used for the flushing analysis presented in Chapter V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic “steady state”, and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

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

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates the total nitrogen concentrations in an estuary as it responds to tidal flushing and nutrient loading, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. The multi-year averages present the “best” comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. Up to 7 years of data (collected between 2001 and 2007) were available for stations in Lake Tashmoo.

Table VI-1. Measured data and modeled nitrogen concentrations for the Lake Tashmoo estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of all measurements. Data represented in this table were collected in the summers of 2001 through 2007.

Sub-Embayment	Monitoring station	Data Mean	s.d. all data	N	model min	model max	model average
Lower Basin	MV21	0.314	0.047	29	0.279	0.327	0.300
Lower Basin	MV1	0.306	0.068	28	0.283	0.343	0.311
Lower Basin	MV2	0.301	0.069	28	0.294	0.356	0.329
Mid-Upper Basin	MV3	0.343	0.071	38	0.356	0.379	0.369
Mid-Upper Basin	MV4	0.360	0.065	37	0.379	0.391	0.385
Upper Basin	MV5	0.447	0.087	37	0.418	0.428	0.423
Offshore	MV6	0.270	0.065	60	-	-	-

VI.2 MODEL DESCRIPTION AND APPLICATION

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of nitrogen loading in the Lake Tashmoo estuarine system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of Lake Tashmoo. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. The MEP Technical Team has utilized this model in water quality studies of other embayment systems in southeastern Massachusetts, including Pleasant Bay (Howes *et al*., 2006); New Bedford Harbor (Howes *et al*., 2008) and Edgartown Great Pond, MA (Howes *et al*., 2008).

The overall approach involves modeling total nitrogen as a non-conservative constituent, where bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. This modeling represents summertime conditions, when algal growth is at its maximum. Total nitrogen modeling is based upon various data collection efforts and analyses presented in previous sections of this report. Nitrogen loading information was derived from the watershed loading analysis of Section IV, as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements were utilized as model boundaries and as calibration data. Hydrodynamic model output (discussed in Section V) provided the remaining information (tides, currents, and bathymetry) needed to parameterize the water quality model of the Lake Tashmoo system.

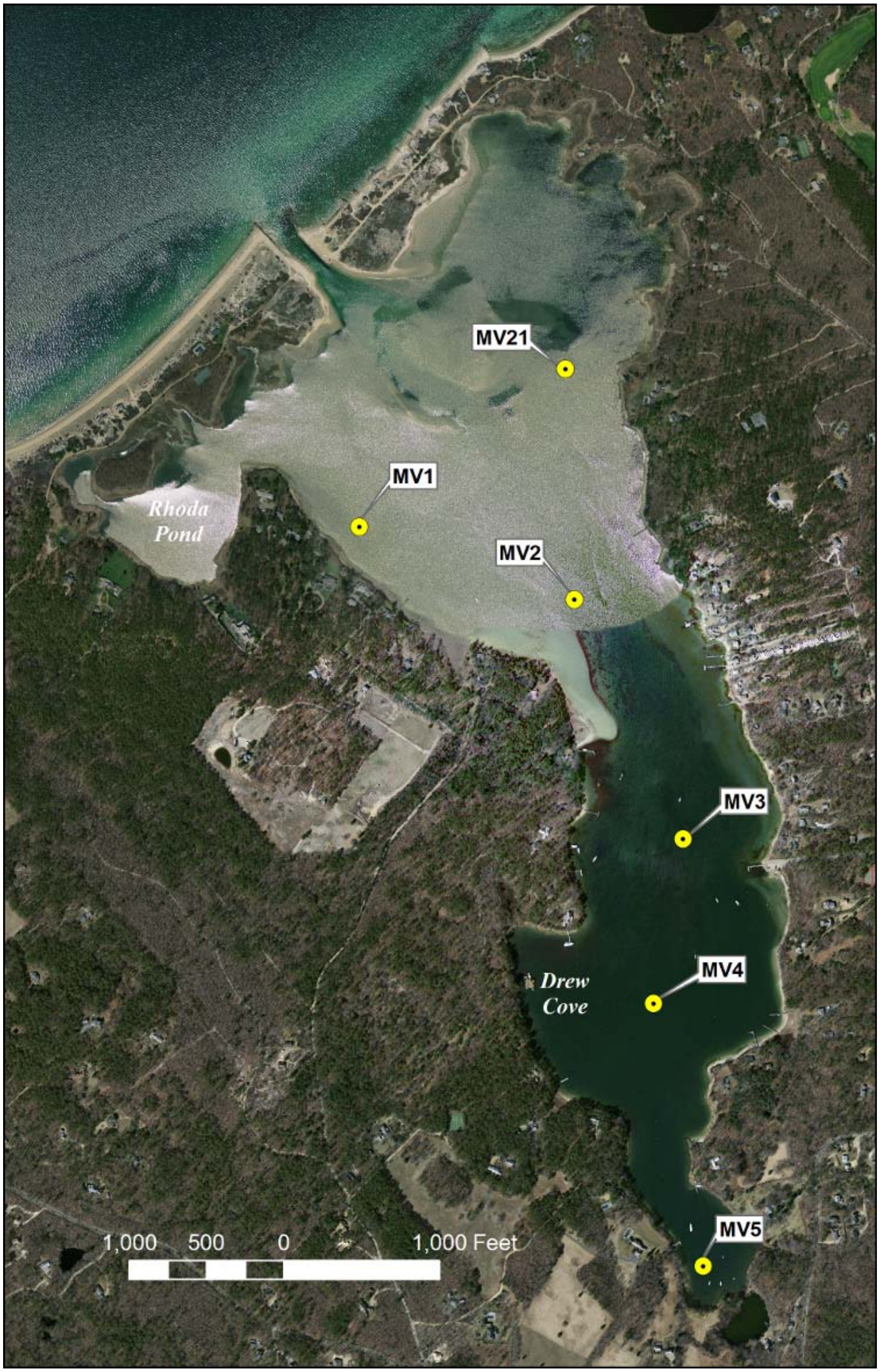

Figure VI-1. Estuarine water quality monitoring station locations in the Lake Tashmoo estuary system. Station labels correspond to those provided in Table VI-1.

VI.2.1 Model Formulation

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

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

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

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

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

VI.2.2 Water Quality Model Setup

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

For each model run, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 14 day (336 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input.

VI.2.3 Boundary Condition Specification

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

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

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in Vineyard Sound, offshore the pond inlet, was set at 0.270 mg/L, based on SMAST monitoring data.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Lake Tashmoo – main basin	19.907	3.304	8.750
Drew Cove	4.433	0.504	7.765
Lake Tashmoo - upper	0.764	-	-
System Total	25.104	3.808	16.515

VI.2.4 Model Calibration

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

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

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

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

Embayment Division	E m^2/sec
Brown Point	1.0
Drew Cove	1.5
Hullman Point	5.0
Lake Tashmoo - Main Basin	5.0
Rhoda Pond	5.0
Offshore	10.0
Inlet channel	10.0

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for each system. The computed R^2 correlation is 0.81 and the root mean squared (rms) error is 0.02 mg/L, which demonstrate an excellent fit between modeled and measured data for this system.

A contour plot of calibrated model output is shown in Figure VI-4. In this figure, color contours indicate nitrogen concentrations throughout the model domain. The output in these figures show average total nitrogen concentrations, computed using the full 14-tidal-day model simulation output period.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Lake Tashmoo system using salinity data collected at the same stations as the nitrogen data. For the salinity verification, none of the model dispersion coefficients were changed from the values used in the TN calibration. Comparisons of modeled and measured salinities are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. The RMS error of the model is 1.0 ppt.

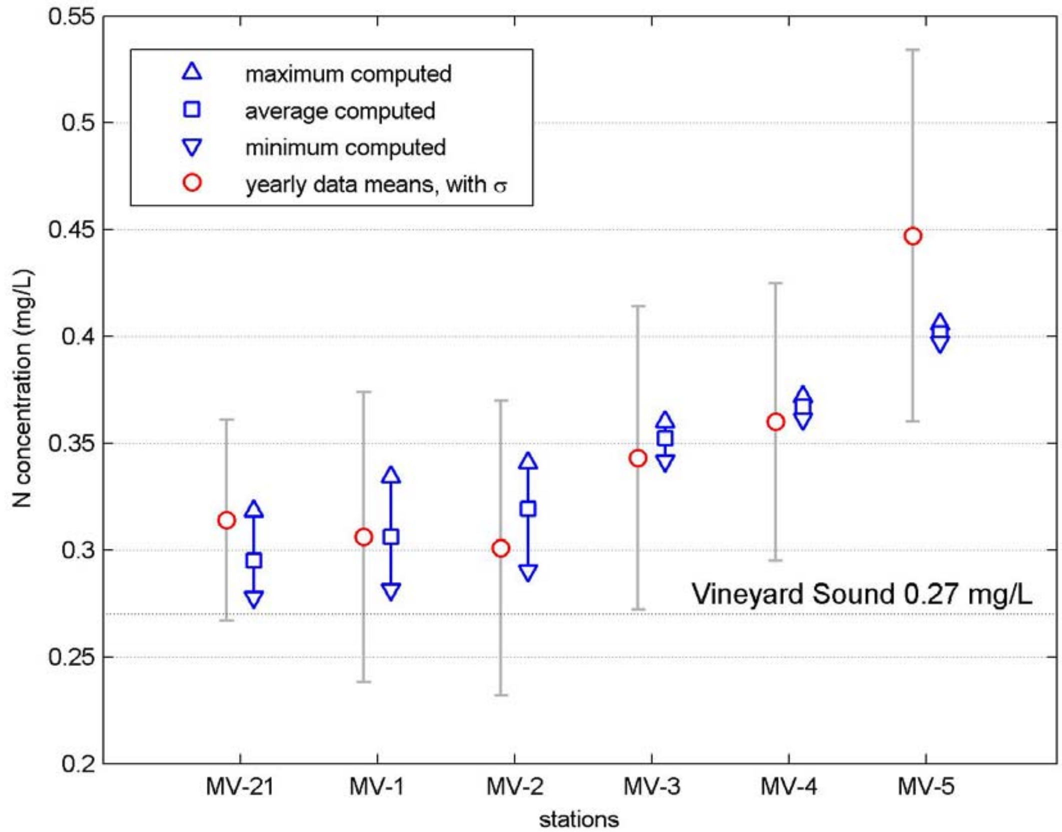

Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Lake Tashmoo system. Station labels correspond with the MEP IDs provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation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

The only required inputs into the RMA4 salinity model of the system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, rain, surface water and groundwater inputs. The open boundary salinity was set at 31.2 ppt. All groundwater input salinities were set at 0 ppt. Groundwater flows to the pond included in the model were 7.05 ft^3/sec (15,400 m^3/day) for the main basin of Lake Tashmoo, 2.18 ft^3/sec (5,050 m^3/day) for the Drew Cove and 0.42 ft^3/sec (1,040 m^3/day) at the head of Lake Tashmoo. Average rainfall rates included in the simulation were 0.76 ft^3/sec (1,860 m^3/day) for the main basin and 0.12 ft^3/sec (280 m^3/day) for Drew Cove. Groundwater and rainfall flows were distributed evenly in the model along elements positioned along the model's land boundary.

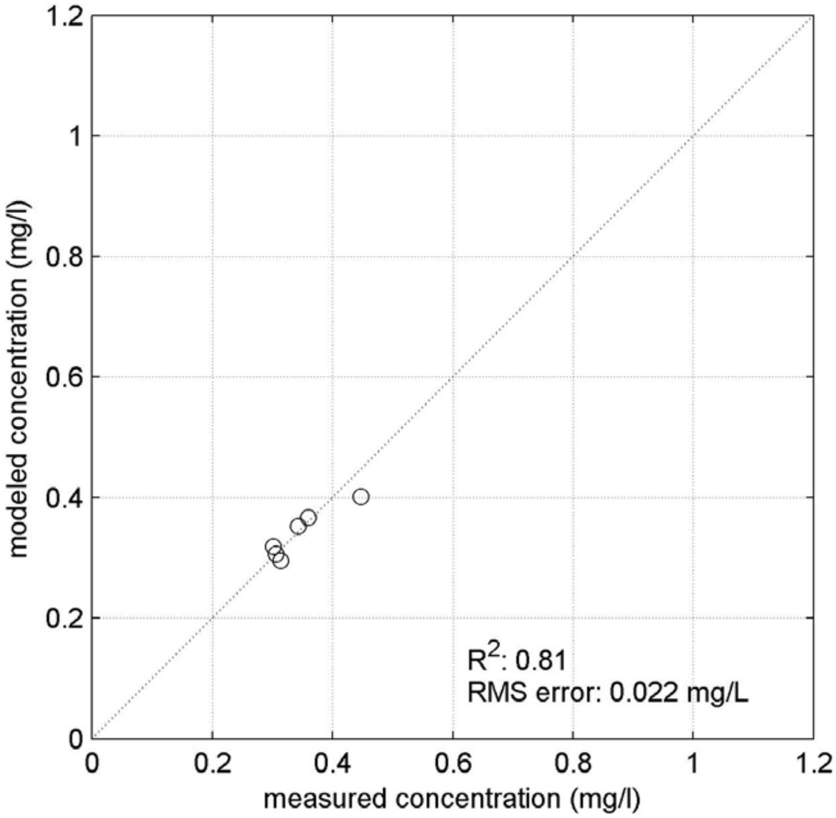

Figure VI-3. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are 0.81 and 0.022 mg/L respectively. The 0.81 R^2 value for the Lake Tashmoo model is indicative of a good fit between measured data and model output. The R^2 coefficient determined for the Lake Tashmoo model is influenced by the number of WQ stations in the pond and relatively small gradient in TN concentrations between the inlet and upper inland reaches. Higher R^2 values are generally easier to achieve in systems with a larger spread in TN concentrations. The model calibration is always determined as the best fit between all the various WQ model inputs and the measured WQ data.

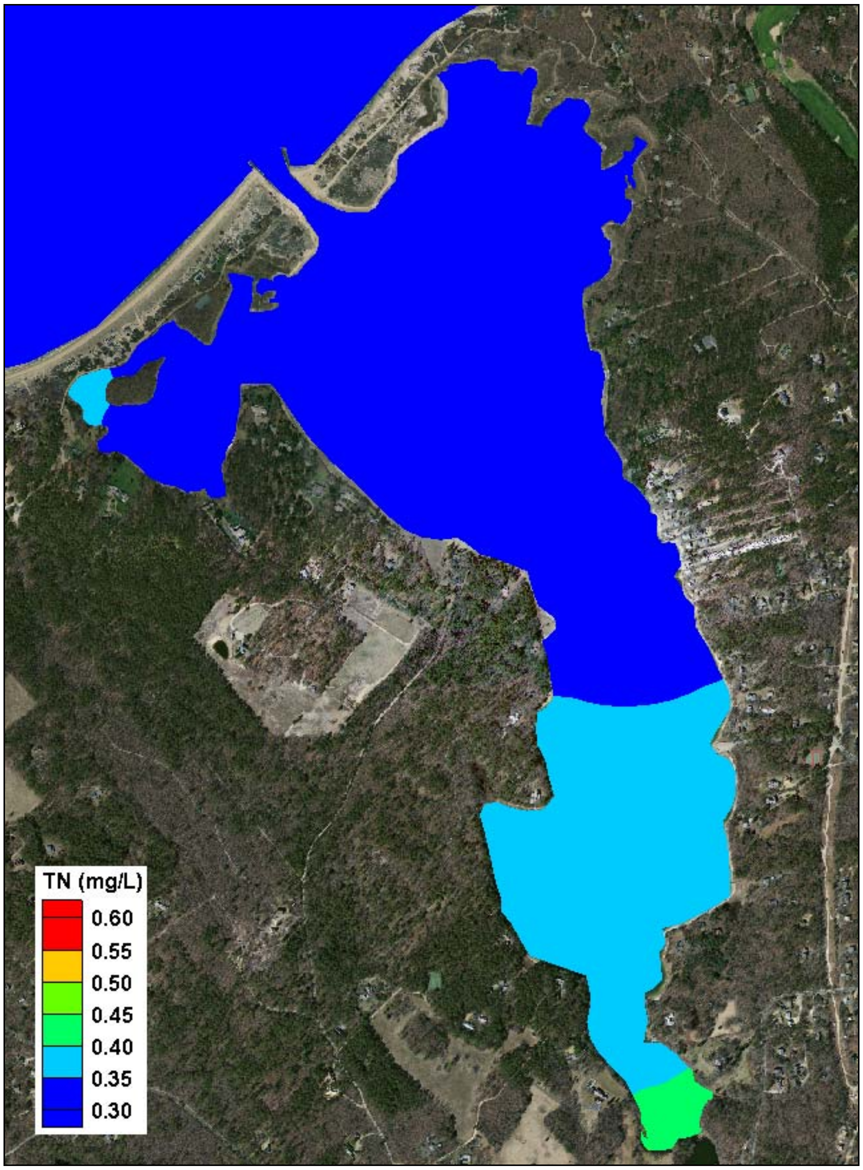

Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Lake Tashmoo system.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

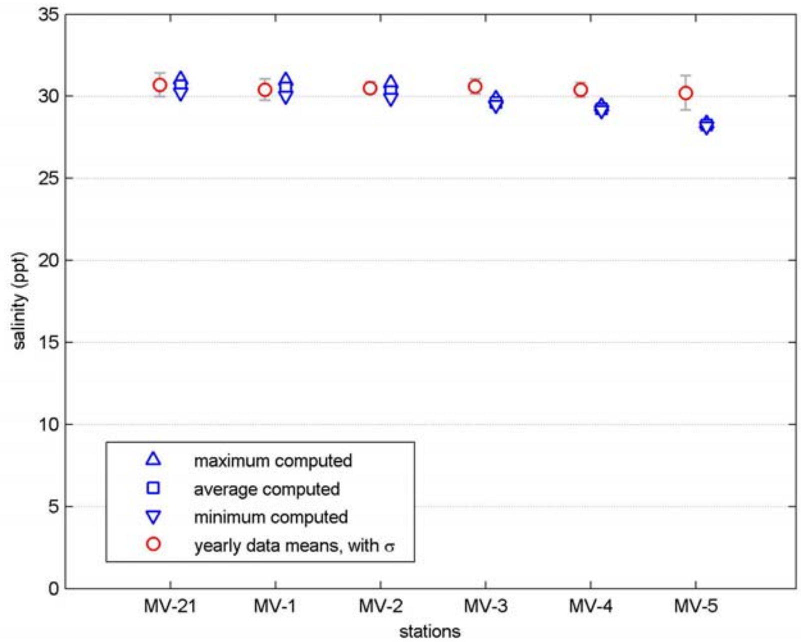

Figure VI-5. Comparison of measured and calibrated model output at stations in Lake Tashmoo. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with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

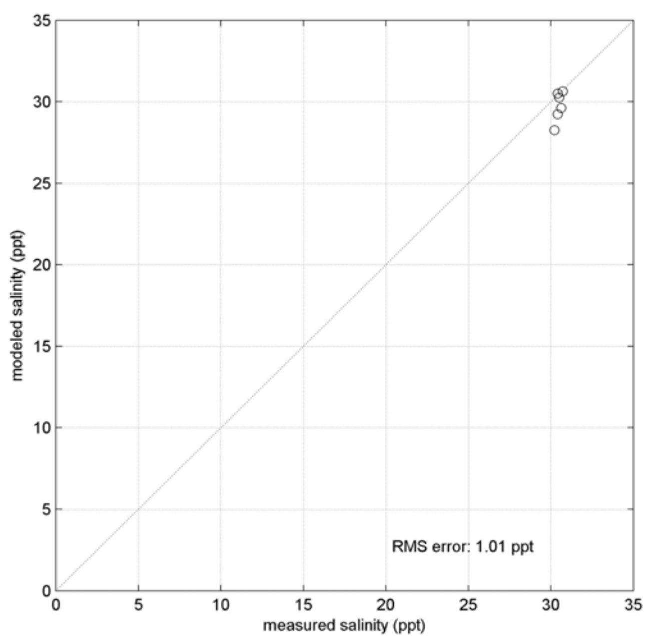

Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. RMS error for this model verification run is 1.01 ppt.

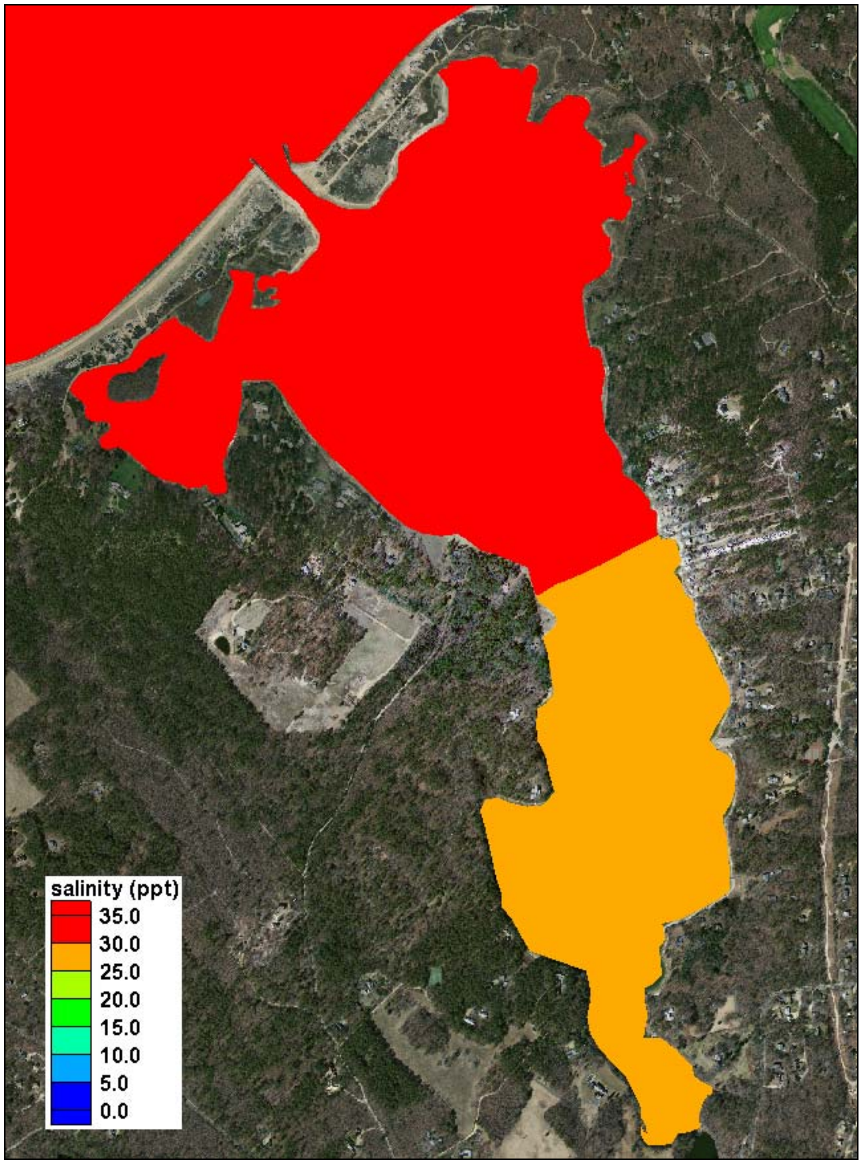

Figure VI-7. Contour Plot of average modeled salinity (ppt) in the Lake Tashmoo system.

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Lake Tashmoo system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	Build-out (kg/day)	build-out % change	no load (kg/day)	no load % change
Lake Tashmoo – main basin	19.907	29.523	+48.3%	1.460	-92.7%
Drew Cove	4.433	5.742	+29.5%	0.496	-88.8%
Lake Tashmoo - upper	0.764	0.907	+18.6%	0.096	-87.5%
System Total	25.104	36.173	+44.1%	2.052	-91.8%

VI.2.6.1 Build-Out

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

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Table VI-5. **Build-out** scenario sub-embayment and surface water loads used for total nitrogen modeling of the Lake Tashmoo system, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Lake Tashmoo – main basin	29.523	3.304	9.961
Drew Cove	5.742	0.504	8.801
Lake Tashmoo - upper	0.907	-	-
System Total	36.173	3.808	18.762

Following development of the nitrogen loading estimates for the build-out scenario, the water quality models of the system was run to determine nitrogen concentrations at each monitoring station (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Vineyard Sound) remained identical to the existing conditions modeling scenarios. For build-out, the increase in modeled TN concentrations is greatest at the monitoring station MV1, in the main basin of the pond, where concentrations increase more than 18%. A contour plot showing average TN concentrations throughout the Lake Tashmoo system is presented in Figure VI-8 for the modeling of build-out loads.

Table VI-6. Comparison of model average total N concentrations from present loading and the **build-out scenario**, with percent change over background in Vineyard Sound (0.270 mg/L), for the Lake Tashmoo system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out (mg/L)	% change
Tashmoo - main basin	MV21	0.300	0.304	+15.4%
Tashmoo - main basin	MV1	0.311	0.319	+18.1%
Tashmoo - main basin	MV2	0.329	0.338	+14.4%
Tashmoo - main basin	MV3	0.369	0.383	+14.3%
Drew Cove	MV4	0.385	0.402	+14.9%
Upper Lake Tashmoo	MV5	0.423	0.446	+14.9%

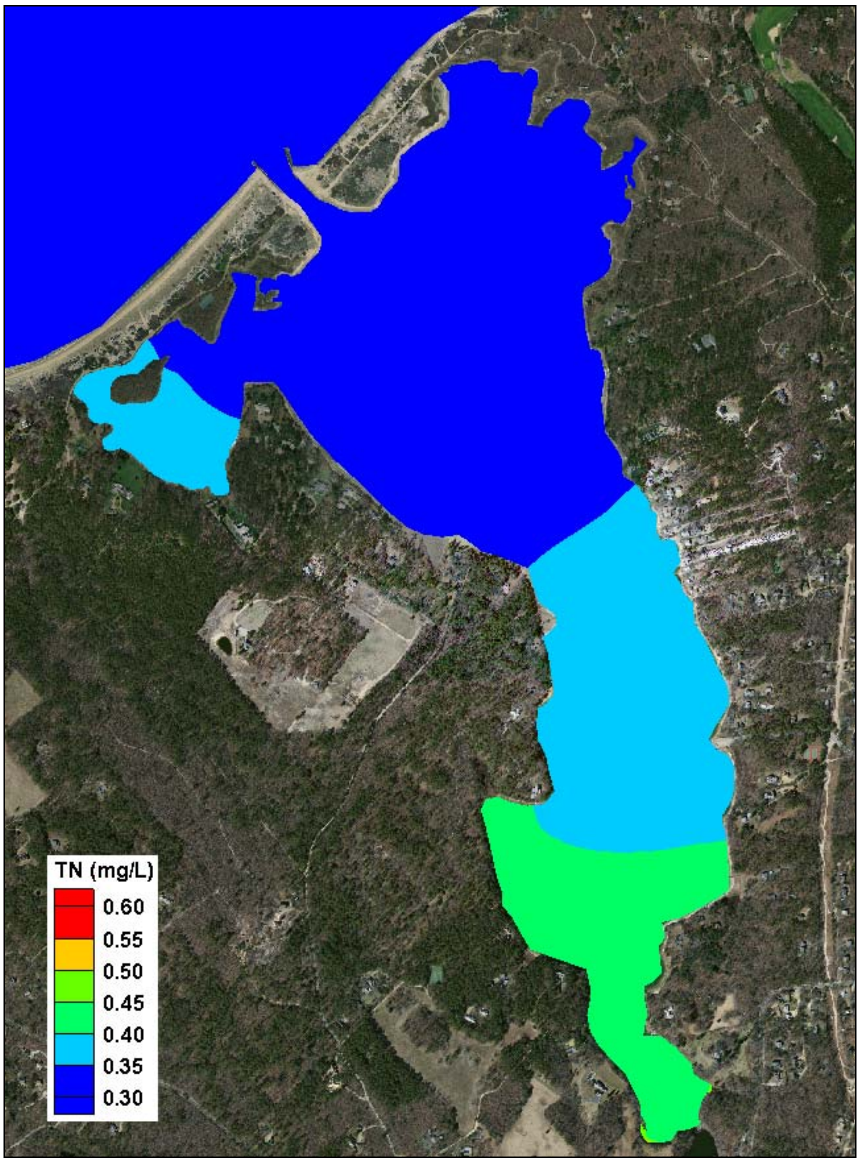

Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Lake Tashmoo system, for projected build-out scenario loading conditions.

VI.2.6.2 No Anthropogenic Load

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

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Lake Tashmoo – main basin	1.460	3.304	5.990
Drew Cove	0.496	0.504	5.091
Lake Tashmoo - upper	0.096	-	-
System Total	2.052	3.808	11.081

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations at each monitoring station. Similar to the procedure followed for the build-out simulation, total nitrogen concentrations in the receiving waters (i.e., Vineyard Sound) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was large, with all areas of the system experiencing reductions greater than 78%, compared to the background concentration of 0.270 in Vineyard Sound (Table VI-8). A contour plot showing TN concentrations throughout the system is shown pictorially in Figure VI-9.

Table VI-8. Comparison of model average total N concentrations from present loading and the "**No anthropogenic loading**" ("no load"), with percent change over background in Vineyard Sound (0.270 mg/L), for the Lake Tashmoo system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	no-load (mg/L)	% change
Tashmoo - main basin	MV21	0.300	0.275	-82.2%
Tashmoo - main basin	MV1	0.311	0.279	-78.7%
Tashmoo - main basin	MV2	0.329	0.280	-83.9%
Tashmoo - main basin	MV3	0.369	0.285	-84.6%
Drew Cove	MV4	0.385	0.288	-84.5%
Upper Lake Tashmoo	MV5	0.423	0.292	-85.7%

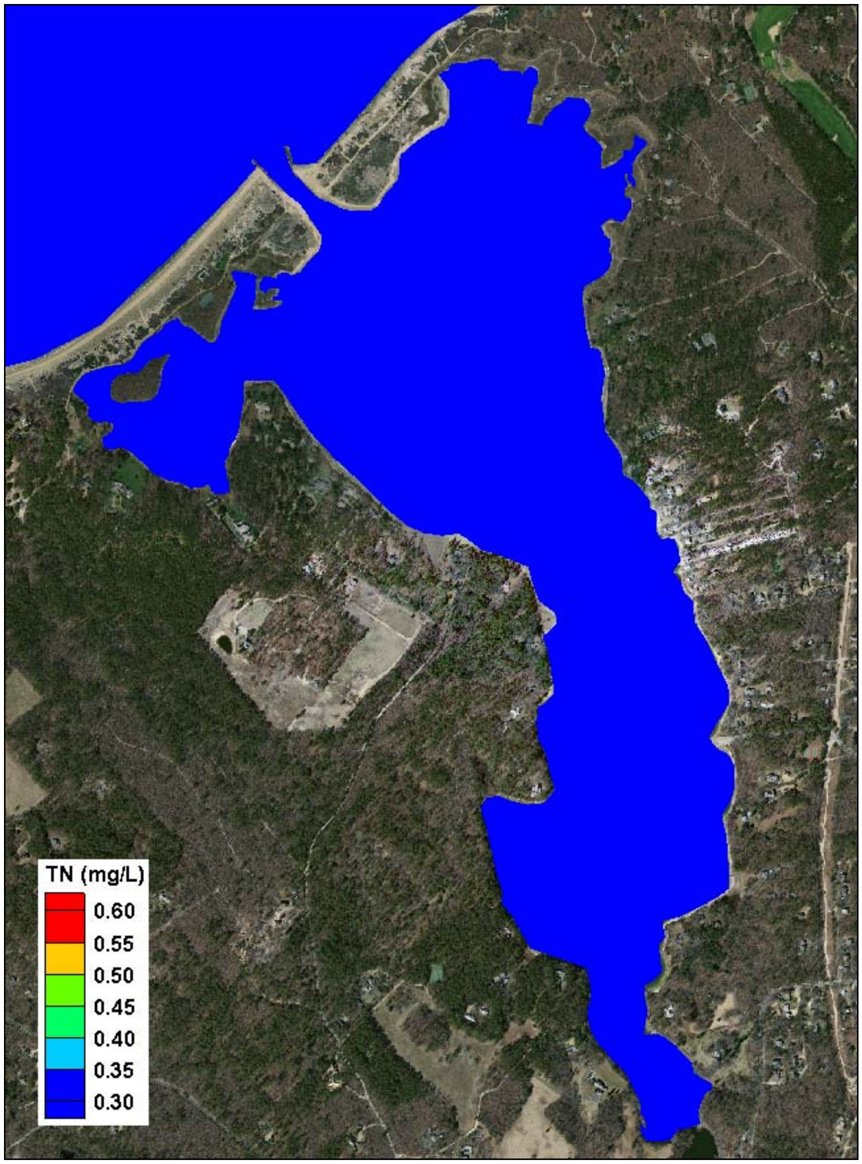

Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in Lake Tashmoo, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Lake Tashmoo embayment system in the Town of Tisbury, MA, the assessment is based upon: 1) data from the water quality monitoring baseline developed by the Martha's Vineyard Commission, the Town of Tisbury and SMAST staff, 2) surveys of eelgrass distribution by MVC and MassDEP, 3) benthic animal communities and sediment characteristics and 4) dissolved oxygen records conducted during the summer and fall of 2003. These data form the basis of the assessment of this system's ecological health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for this system (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen threshold determination, the MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll-*a* (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed dissolved oxygen sensors within the Lake Tashmoo Estuary at points that would be representative of dissolved oxygen conditions in the main Lake Tashmoo basin (north), as well as the upper terminal basin of the system (south). The two 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 Lake Tashmoo system was conducted to assess recent temporal trends in coverage (MassDEP Eelgrass Mapping Program, C. Costello). These coverages were compared to an early MVC survey using a different methodology, to further evaluate changes in eelgrass coverage (Wilcox and Hempy, 1997). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the Lake Tashmoo Estuary, temporal changes in eelgrass distribution provided a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing through inlet) in nutrient enrichment.

In areas that do not support eelgrass beds, benthic animal indicators were used to assess the level of habitat health from “healthy” (low organic matter loading, high D.O.) to “highly stressed” (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of their habitat. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life-history information on the species and a wide variety of field studies within southeastern Massachusetts waters, including the Wild Harbor oil spill, benthic population studies in Buzzards Bay (Woods Hole Oceanographic Institution) and New Bedford (SMAST), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H’) and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 4.0 mg L^{-1} in open water estuarine environments. Massachusetts State Water Quality Classifications indicate that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Lake Tashmoo 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 estuaries 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 the upper and lower regions of the Lake Tashmoo 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 early-September during the summer of 2003.

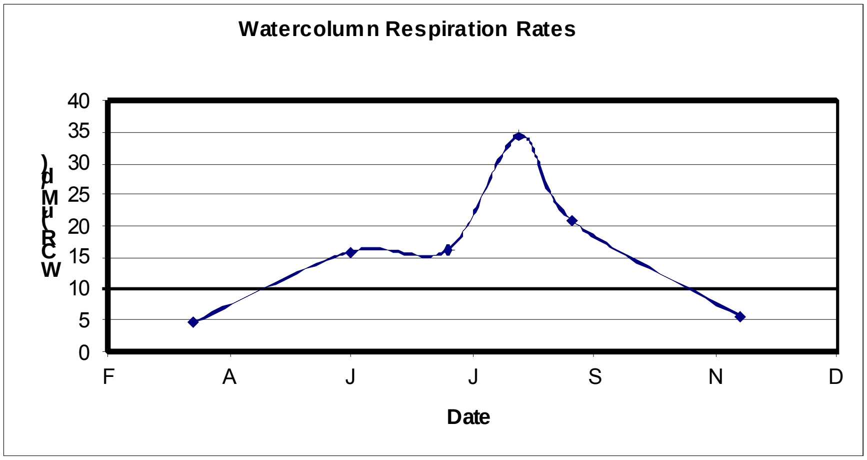

Figure VII-1. Average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Lake Tashmoo Estuary evaluated in this assessment showed high frequency variation, apparently related to diurnal and 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 (4-6 mg/L) within the upper pond (Brown Point mooring) along with periodic hypoxia underscores the need for continuous monitoring within these systems.

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 32 day (Lake Tashmoo lower {Hilman Point} and upper {Brown Point}) deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

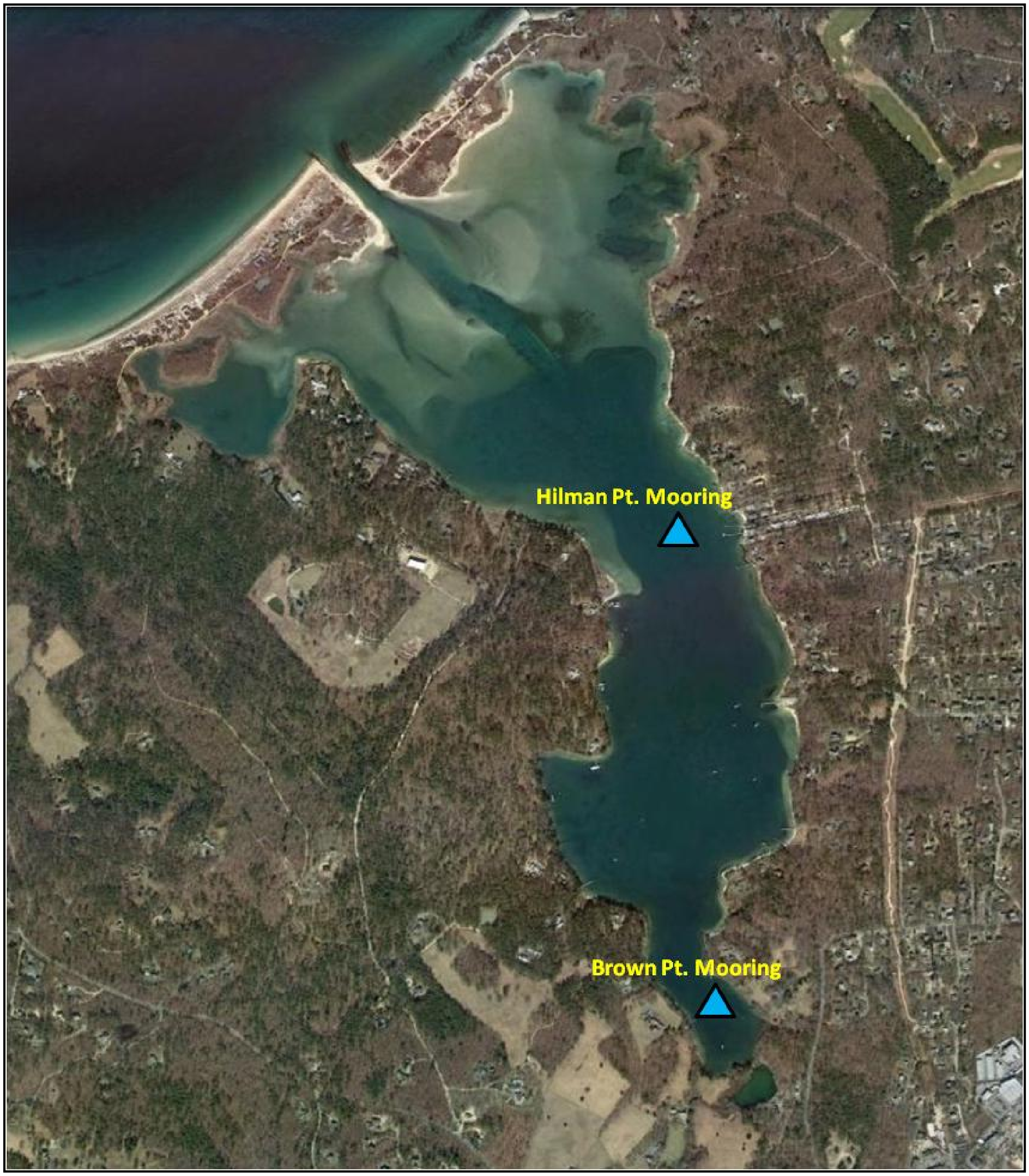

Figure VII-2. Aerial Photograph of the Lake Tashmoo system in the Town of Tisbury showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2003.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate conditions of moderate habitat quality at the Hilman Point and moderate to poor habitat quality at the Brown Point mooring sites respectively (Figures VII-3 through VII-6). The chlorophyll-*a* levels indicate only moderate nitrogen enrichment, while the bottom water oxygen levels show periodic hypoxia at upper pond location. It is likely that the effects of nitrogen enrichment (0.45 mg/L) on oxygen levels in the upper basins is enhanced by periodic short-term stratification in the deep waters of the upper basin. The oxygen data are consistent with organic matter enrichment, primarily from phytoplankton production which shows blooms to 10-20 mg/L (Water Quality Monitoring Program). The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follow the spatial pattern of total nitrogen levels in this system (Chapter VI) and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuary. However, it is clear that nutrient enrichment response in Lake Tashmoo Pond is magnified by its basin structure, which when combined with the depositional nature of the upper region (head water to Hilman Point) and accumulations of macroalgae, results in poor quality benthic animal habitat within the deeper water of the upper basin (TMO1-TMO6, 3.15 meters total depth), see Section VII-4. The loss of eelgrass in the uppermost tidal reaches is almost certainly a result of its depth and depositional nature (unconsolidated fluid muds).

Measured dissolved oxygen depletion indicates that the southern (upper) region of Lake Tashmoo shows high levels of oxygen stress whereas the northern (lower) region shows low to moderate levels of oxygen stress. This is seen clearly in the data record collected from the autonomous oxygen recorders deployed in the upper and mid pond regions (Figure VII-2). 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. The pattern of oxygen depletion, levels of chlorophyll-*a* and nitrogen concentrations are consistent with the observed pattern of eelgrass loss (Section VII.3). Additionally, the pattern of temporal loss is consistent with an estuarine system that is just beyond its ability to assimilate nitrogen loads without impairment. Similarly, infaunal habitats (Section VII.4) also appear to be impaired by organic matter enrichment resulting from nitrogen loading, with the level of habitat impairment being greater in deep versus shallow water. The embayment specific results are as follows:

Lake Tashmoo Mid Estuary (Hilman Point) (Figures VII-3 and VII-4):

The Lake Tashmoo lower mooring site was located mid-channel within the mid basin of the estuary (Figure VII-2). Generally, the daily excursions in oxygen at this location were moderate, showing daily ranges generally of only ~4 mg L^{-1}. Oxygen levels varied primarily with light (diurnal cycle) and to a lesser extent with tidal exchange (tidal cycle). Lowest oxygen was generally observed in the early morning and highest dissolved oxygen was observed towards the end of the photocycle (ca. 1500 hrs). This pattern is typical of virtually all estuaries in southeastern Massachusetts. While maximum oxygen levels did not exceed air equilibration (% air saturation) during the majority of the deployment period, which occurs when nutrient enrichment has stimulated phytoplankton production and oxygen release, a moderate phytoplankton bloom was observed over the last 10 days of the deployment period which corresponds to higher daily fluctuations in oxygen concentrations over the last 5 days of the deployment period. Both the moderate oxygen levels (4 to 7 mg L^{-1}), the moderate daily excursion and the moderate to high chlorophyll levels suggests that moderately organic matter enriched conditions are extant in this region of the basin. Oxygen minima compared well with the Water Quality Monitoring Program that only measures ~ 5 days per year, which showed a minimum of 5.4 - 5.9 mg L^{-1} in the region of Hilman Point versus ~4 at the mooring site. The reason for the slight difference likely stems from the deeper sampling depth by the mooring and the capture of the daily minimum by the mooring versus the grab sampling program.

Oxygen levels were generally above 6 mg L^{-1} (44% of record) and above 5 mg L^{-1} for 87% of the 32 day record (Figure VII-3 and Table VII-1). These "typical values" were very similar to the results from the long-term Water Quality Monitoring Program sampling at this location.

Oxygen levels in the lower portion of the overall system were virtually always >4 mg L^{-1} as seen in the mooring and monitoring results, 4 mg L^{-1} being the critical threshold for oxygen stress in an estuarine systems (Table VII-1). Oxygen levels typically exceeded 6 mg L^{-1} for a portion of each daily record. The infrequent oxygen declines were generally consistent with the low to moderate levels of phytoplankton biomass as measured by chlorophyll-*a* for the first 20 days of the deployment period. Moreover, the greater fluctuation in the oxygen record in the last 12 days of the deployment period corresponded well with the observed increases in the Chlorophyll record. Chlorophyll-*a* averaged 5.1 ug L^{-1} over the record and exceeded 10 ug L^{-1} only 6% of the deployment 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 seldom surpassed by the chlorophyll-*a* observed in this basin of Lake Tashmoo (Table VII-2, Figure VII-4).

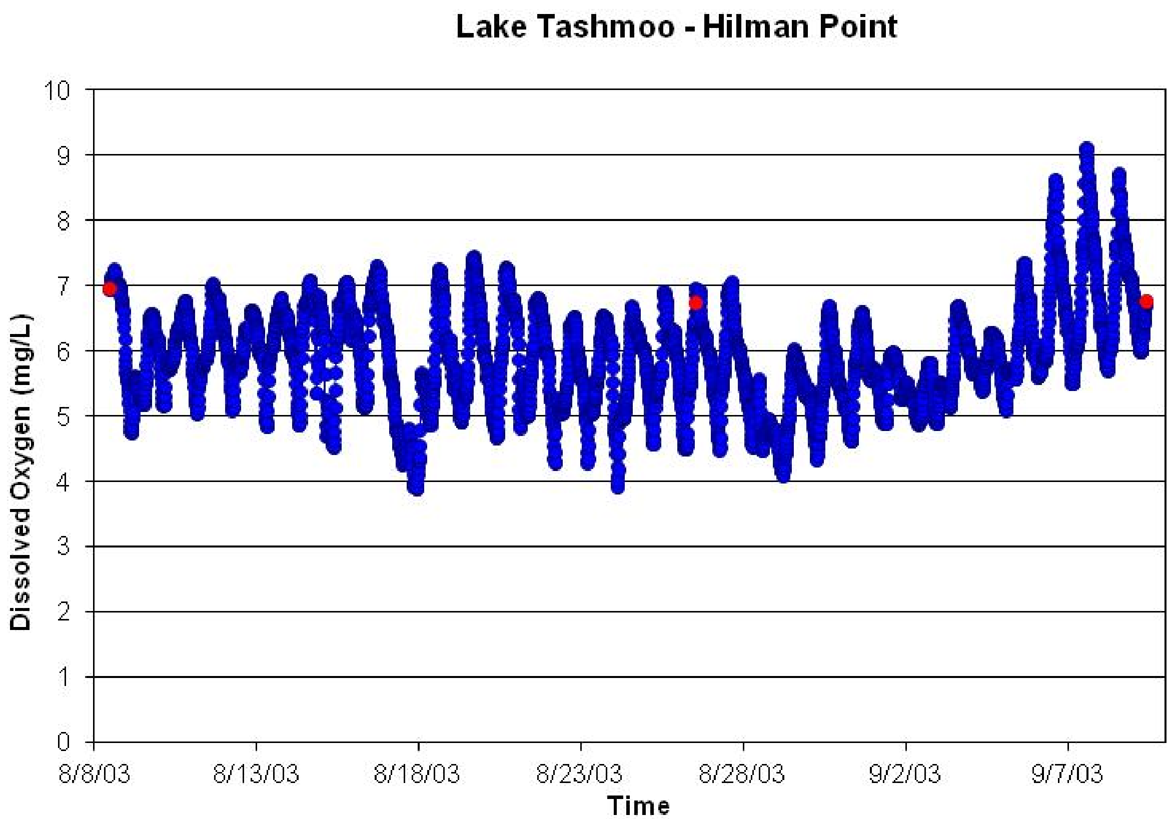

Figure VII-3. Bottom water record of dissolved oxygen at the Lake Tashmoo (Hilman Point station), Summer 2003 (Figure VII-2). Calibration samples represented as red dots.

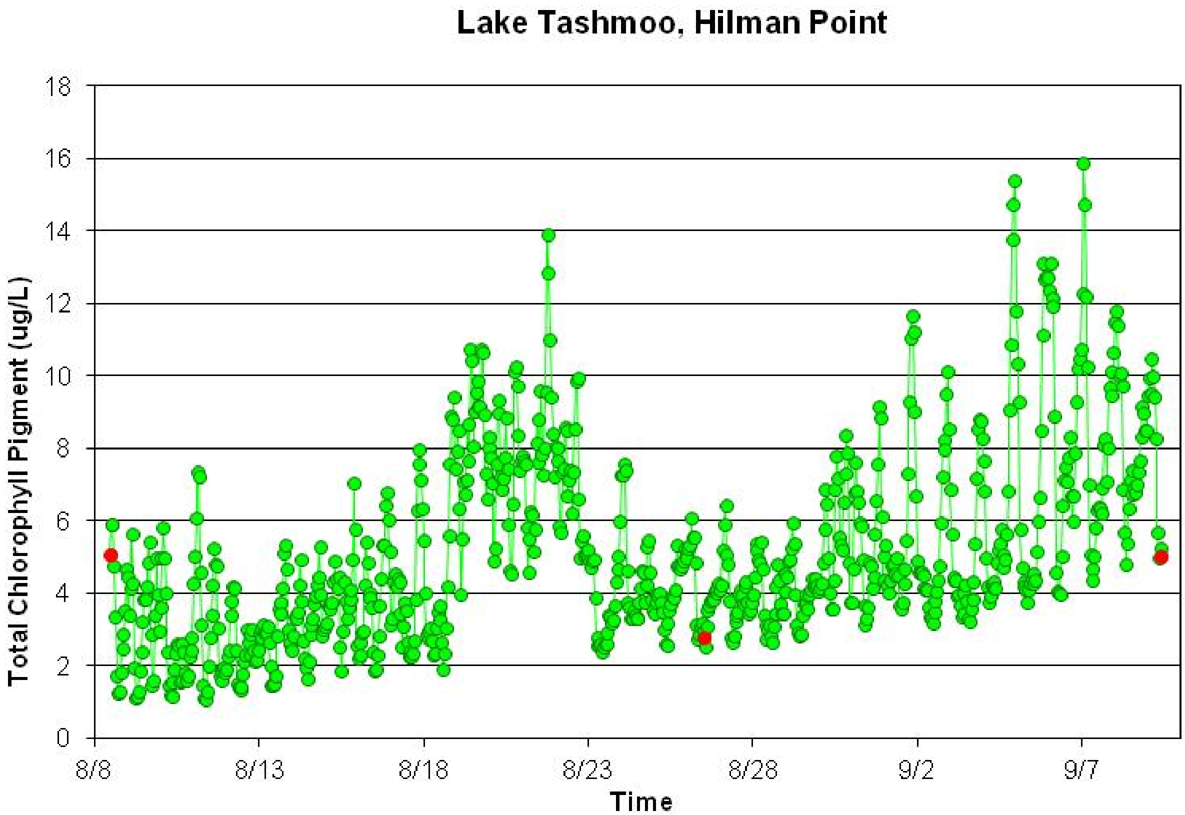

Figure VII-4. Bottom water record of Chlorophyll-*a* in the Lake Tashmoo (Hilman Point station), Summer 2003. Calibration samples represented as red dots.

Lake Tashmoo Upper Tidal Reach (Brown Point station) (Figures VII-5 and VII-6):

The Lake Tashmoo upper mooring site (Brown Point station) was centrally located within the upper deep basin which dominates this southern most tidal reach of the Lake Tashmoo Estuary (Figure VII-2). Generally, the daily excursions in oxygen levels at this location were moderate to high in that the range of the excursions was 3-4 mg L^{-1} in the initial ~20 days of the record, but was ~ 8 mg L^{-1} for the final third of the record, most likely due to a short-term reduction in vertical mixing. This high daily excursion in oxygen level is indicative of a nitrogen enriched system where high phytoplankton production during the day raises oxygen levels higher than atmospheric equilibration and respiration at night lowers oxygen to hypoxic levels. Although oxygen varied with light (diurnal cycle) and the tide stage, the major influence was light (diurnal cycle). Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed when low tide occurred at the end of the photocycle (ca. 1500 hrs). Oxygen levels were regularly less than 6 mg L^{-1} (81 % of record) and <3 mg L^{-1} 30% of the record, periodically reaching hypoxic levels (Table VII-1, Figure VII-5). Oxygen levels were in excess of air equilibration with greater frequency in the last 12 days of the deployment period, coinciding with the period of highest daily excursion. Chlorophyll-*a* indicated a bloom period of phytoplankton in the initial 20 days, where levels generally ranged from ~4 ug L^{-1} to ~12 ug L^{-1}. This initial phytoplankton bloom event in the uppermost portion of the Lake Tashmoo system likely provided the organic matter for the subsequent low oxygen period as the bloom senesced. The upper basin bloom was followed by a small bloom observed in the lower basin of the pond approximately 12 days into the deployment period. Interestingly, at the Lake Tashmoo upper (southern) mooring location, chlorophyll-*a* levels never exceeded the 15 ug L^{-1} benchmark and only exceeded the 10 ug L^{-1} benchmark 8% of the time (Table VII-2, Figure VII-6). Chlorophyll-*a* averaged 6.2 ug L^{-1} over the 32 day deployment record. Average chlorophyll levels over 10 ug L^{-1} have been used to indicate eutrophic conditions in embayments. The moderate chlorophyll-*a* levels, but mainly the oxygen declines to hypoxic conditions and large daily excursions, clearly indicate nitrogen over enrichment of the upper (southern) reaches of the Lake Tashmoo Estuary.

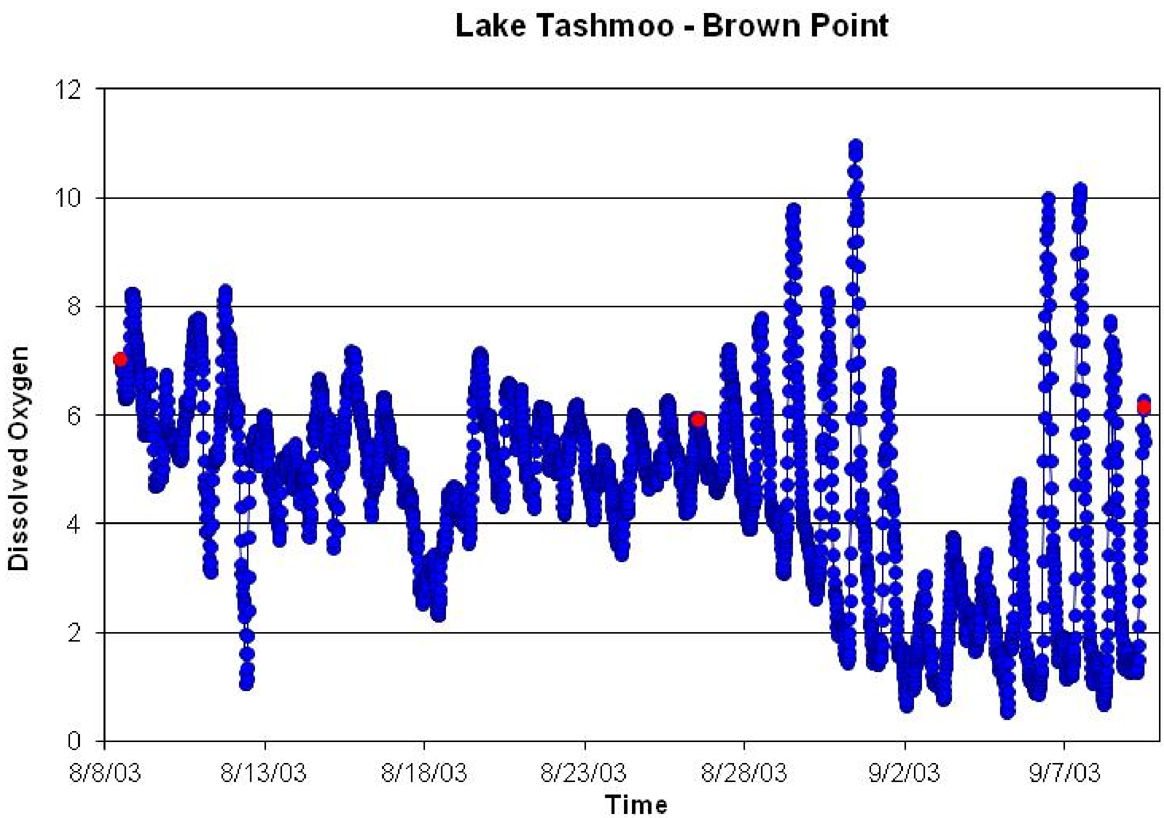

Figure VII-5. Bottom water record of dissolved oxygen at the Lake Tashmoo (Brown Point station), Summer 2003 (Figure VII-2). Calibration samples represented as red dots.

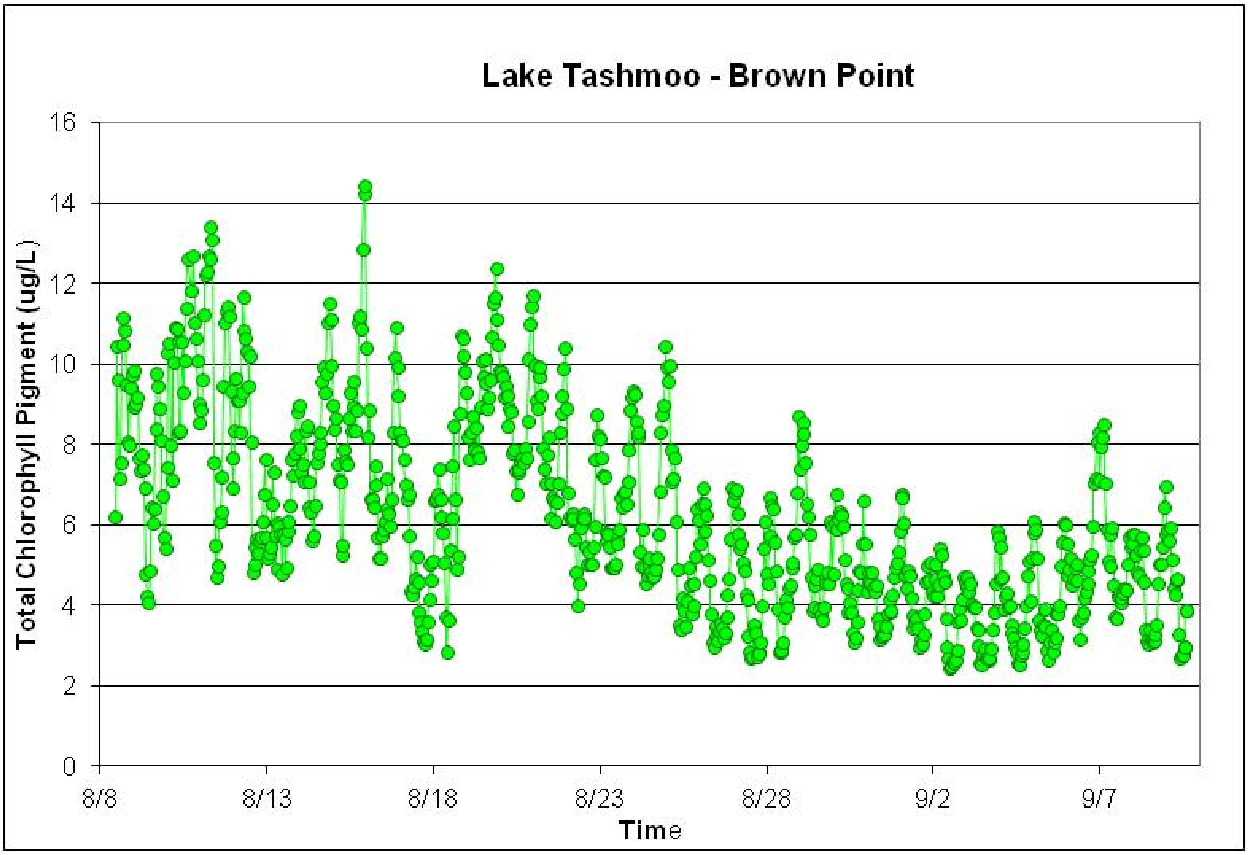

Figure VII-6. Bottom water record of Chlorophyll-*a* in the Lake Tashmoo (Brown Point station), Summer 2003. Calibration samples represented as red dots.

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

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)
Tashmoo Brown Point	**8/8/2003**	**9/9/2003**	**32.0**	**81%**	**56%**	**34%**	**30%**
			Mean	0.89	0.45	0.43	0.48
			Min	0.02	0.01	0.01	0.05
			Max	4.83	4.79	3.80	0.91
			S.D.	0.96	0.81	0.77	0.29
Tashmoo Hilman Point	**8/8/2003**	**9/9/2003**	**32.0**	**56%**	**13%**	**0%**	**0%**
			Mean	0.51	0.18	0.04	N/A
			Min	0.02	0.04	0.02	0.00
			Max	2.69	0.89	0.05	0.00
			S.D.	0.53	0.21	0.02	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)
Lake Tashmoo Brown Point	**8/8/2003**	**9/9/2003**	**32.00**	**62%**	**8%**	**0%**	**0%**	**0%**
Mean Chl Value = 6.2 ug/L			**Mean**	0.48	0.13	N/A	N/A	N/A
			Min	0.04	0.04	0.00	0.00	0.00
			Max	3.71	0.33	0.00	0.00	0.00
			S.D.	0.81	0.10	N/A	N/A	N/A
Lake Tashmoo Hilman Point	**8/8/2003**	**9/9/2003**	**32.00**	**40%**	**6%**	**0%**	**0%**	**0%**
Mean Chl Value = 5.1 ug/L			**Mean**	0.30	0.15	0.04	N/A	N/A
			Min	0.04	0.04	0.04	0.00	0.00
			Max	1.75	0.38	0.04	0.00	0.00
			S.D.	0.35	0.12	0.00	N/A	N/A

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data was conducted for the Lake Tashmoo Embayment System by the MassDEP Eelgrass Mapping Program as part of the MEP. Surveys were conducted in 1995, 2001, 2006-07 and 2010, as part of this program. Additional analysis of available aerial photos from 1951 was undertaken to reconstruct the eelgrass distribution prior to any substantial development of the watershed, as 1951 aerial photographs were available and of sufficient quality. In addition, a survey was undertaken in 1997 by the Martha's Vineyard Commission (Hempy and Wilcox, 1997), to map macrophyte beds, dominated by eelgrass (*Zostera marina*), their health and productivity. The 1997 MVC eelgrass study provided useful information for qualitative comparison to the 1995 MassDEP survey results. The 2010 MassDEP eelgrass map was field validated. The primary use of the data are to indicate: (a) if eelgrass once or currently colonizes Lake Tashmoo basins and (b) if large-scale system-wide shifts have occurred in eelgrass coverage and distribution. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 2010 (Figure VII-7); a period during which watershed nitrogen loading significantly increased to its present level. This temporal information can be used to determine the stability of the eelgrass community.

At present, eelgrass beds exist mainly within the mid-upper basin of the Lake Tashmoo Estuary with smaller beds in the lower portion of the system closest to the inlet. Upper refers to up-gradient (up the hydrologic gradient) and lower refers to down gradient (down the hydrologic gradient). In 1951 eelgrass coverage extended throughout the main basin of the estuary from just up-gradient of Kuffies Point to the uppermost tidal reach near the discharge from the freshwater pond (spring) at the present herring ladder covering ~114 acres. However, both the 1995 MassDEP and 1997 MVC surveys indicate that eelgrass coverage had been lost in the uppermost reach and certainly from the lower portion of the main basin, primarily the deeper waters, but coverage was still significant at ~90 acres. This trend continued to 2001 with additional loss at the lower and upper margins of the main basin beds further reducing coverage to 38 acres, again with loss mainly from deep waters. The coverage has remained relatively constant to 2010, with losses from the upper basin being more than offset by development of a new bed within the channel to the tidal inlet in the lower portion of the estuary, where water depth is shallow and water quality is maintained at a high level by incoming water from Vineyard Sound (Figure VII-7b). It appears that eelgrass is generally present at depths less than 2.5-3.0 meters, consistent with observed light penetration data from the water quality monitoring program (average Secchi depths of ~2.1 m). The pattern of eelgrass loss is consistent with nitrogen enrichment, where increased nitrogen increases phytoplankton biomass which reduces light penetration (Benson and Howes 2013). Lower light penetration results in eelgrass habitat loss from the deep waters and usually from the headwaters as well. It is also almost certain that the observed periodic hypoxia in the uppermost headwater basin resulted in the loss of the beds observed in 1995 and 1997 surveys.

Overall, the observations are diagnostic of a moderate level of nitrogen enrichment, where eelgrass coverage is being reduced over decades in the uppermost tidal basin with elevated nitrogen levels (0.45 mg L^{-1}), a level at which eelgrass has been lost in the 55+ estuaries assessed by the MEP. In addition the eelgrass loss from the deep waters at lower levels of nitrogen enrichment are consistent with observations where lower nitrogen thresholds are required to lower phytoplankton shading of eelgrass beds to allow their persistence within southeastern Massachusetts estuaries.

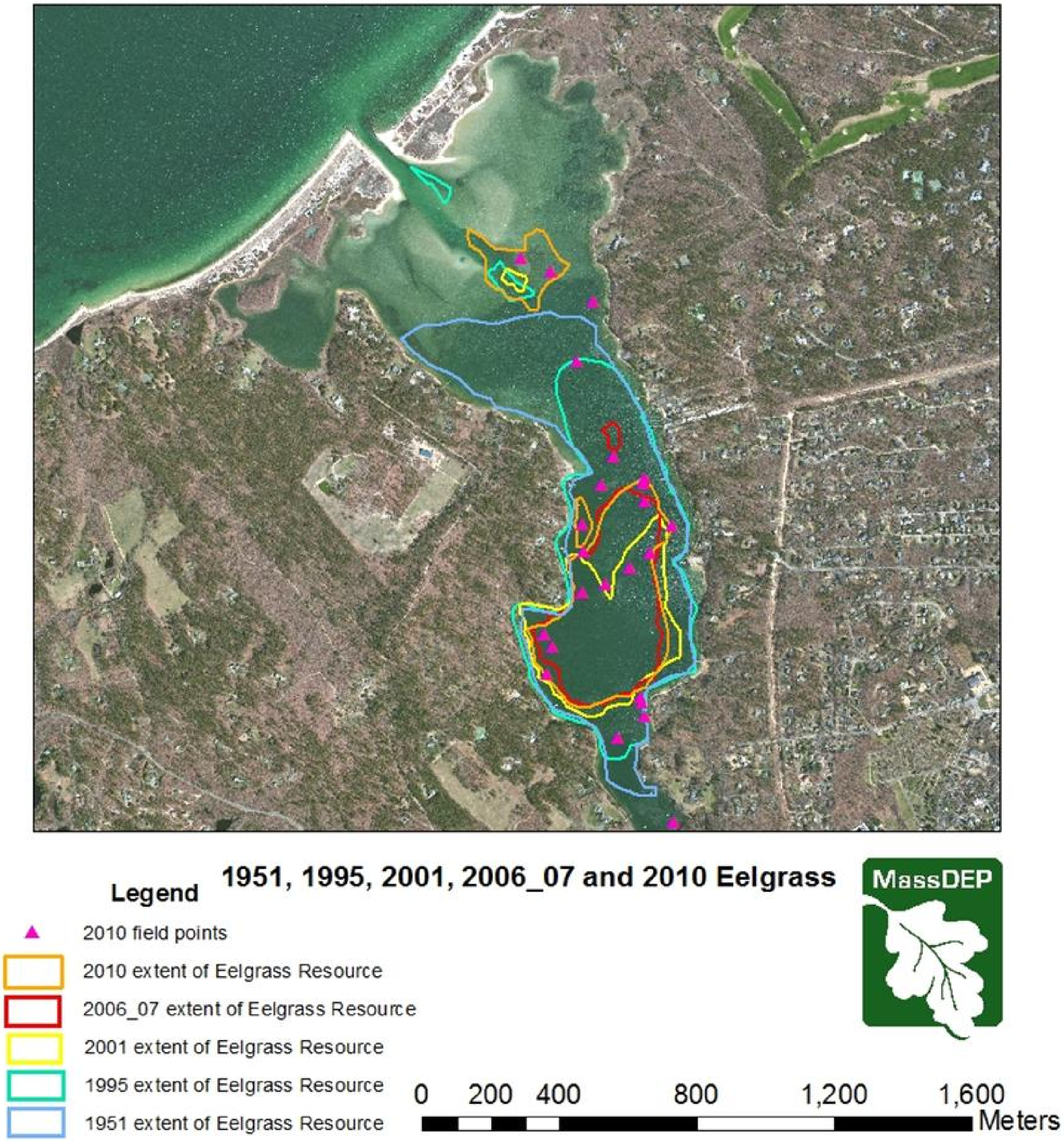

Figure VII-7. Eelgrass bed distribution within the Lake Tashmoo System. The 1951 coverage is depicted in blue outline which circumscribes the beds based on aerial photo interpretation. The 1995 coverage is depicted by the green outline which circumscribes the eelgrass beds based on measured survey, similarly the 2001 (yellow line), 2006 (red line) and 2010 (orange line). Eelgrass areas were surveyed by the MassDEP Eelgrass Mapping Program (C. Costello).

Analysis of nitrogen levels and eelgrass decline indicate that in the uppermost basin where eelgrass has been lost, average total nitrogen (TN) from the multi-year Water Quality Monitoring Program were relatively high, 0.45 mg L^{-1}. The absence of eelgrass in this basin is consistent with that in Lagoon Pond where the level of nitrogen enrichment observed by the monitoring program was 0.386 mg N L^{-1}. In contrast, eelgrass in Lake Tashmoo appears to be relatively stable at a TN level of 0.36 mg N L^{-1} (MV4) but not at 0.386, the tidally averaged TN level within the channel adjacent Brown Point where eelgrass was lost between 1995 and 2001.

The Lagoon Pond system adjacent to Lake Tashmoo is also showing a continuing estuary-wide decline in eelgrass coverage, similar to that in Lake Tashmoo, with losses of beds from the upper basin and from the deeper waters. This pattern of bed loss, where beds appear to retreat from the upper basins toward the inlet and from the deeper to shallower water, is diagnostic of nitrogen enrichment effects in southeastern Massachusetts estuaries. Previous MEP assessments of Cape Cod estuaries indicate that the sensitivity of eelgrass to nitrogen enrichment affects is directly related to water depth. Eelgrass beds in very shallow water (1 meter) are able to tolerate higher nitrogen and chlorophyll-*a* levels and lower light penetration than eelgrass in deeper systems (2-3 meters). This appears to be the case for both Lake Tashmoo and Lagoon Pond, as well.

The persistence of beds in the mid basin suggests that nitrogen enrichment is moderate and that the system is just over its nitrogen threshold, which is also consistent with the observed chlorophyll-*a* levels. However, the losses of bed area from 1995-2006 indicate that nitrogen enrichment is continuing. As the loss of eelgrass in these mid areas is well documented and consistent with nitrogen enrichment, re-establishing these beds should be the target for restoration, as this habitat would be recovered with appropriate nitrogen management. In contrast, there is little evidence of the lowermost portion of the estuary behind the barrier beach ever having had eelgrass habitat, most likely due to unstable sediments and periodic wash over events. Establishment of eelgrass in the lower area of the system cannot be supported as a specific restoration goal.

In the 1997 MVC eelgrass study, the eelgrass beds within Lake Tashmoo were mostly mapped by SCUBA diving along specific transects across the pond (Figure VII-7a). SCUBA diving and snorkeling was done in order to visually assess the eelgrass beds, shallow areas were mapped using a view box (glass bottom wooden box). Surveying was completed between July 1 and July 28, 1997.

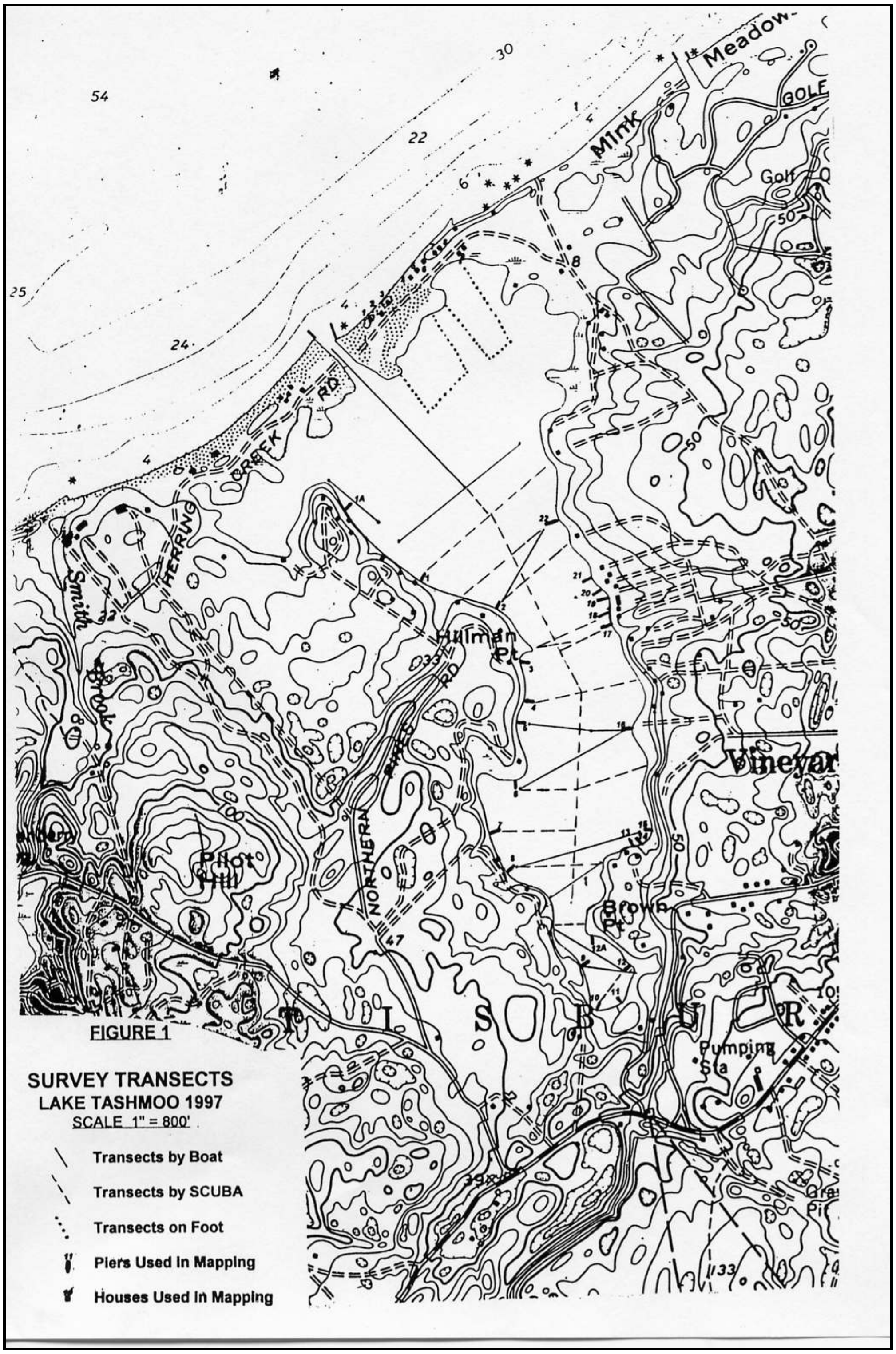

Figure VII-7a. Survey transects for determining eelgrass bed distribution within the Lake Tashmoo System in 1997 (Wilcox and Hempy, 1997).

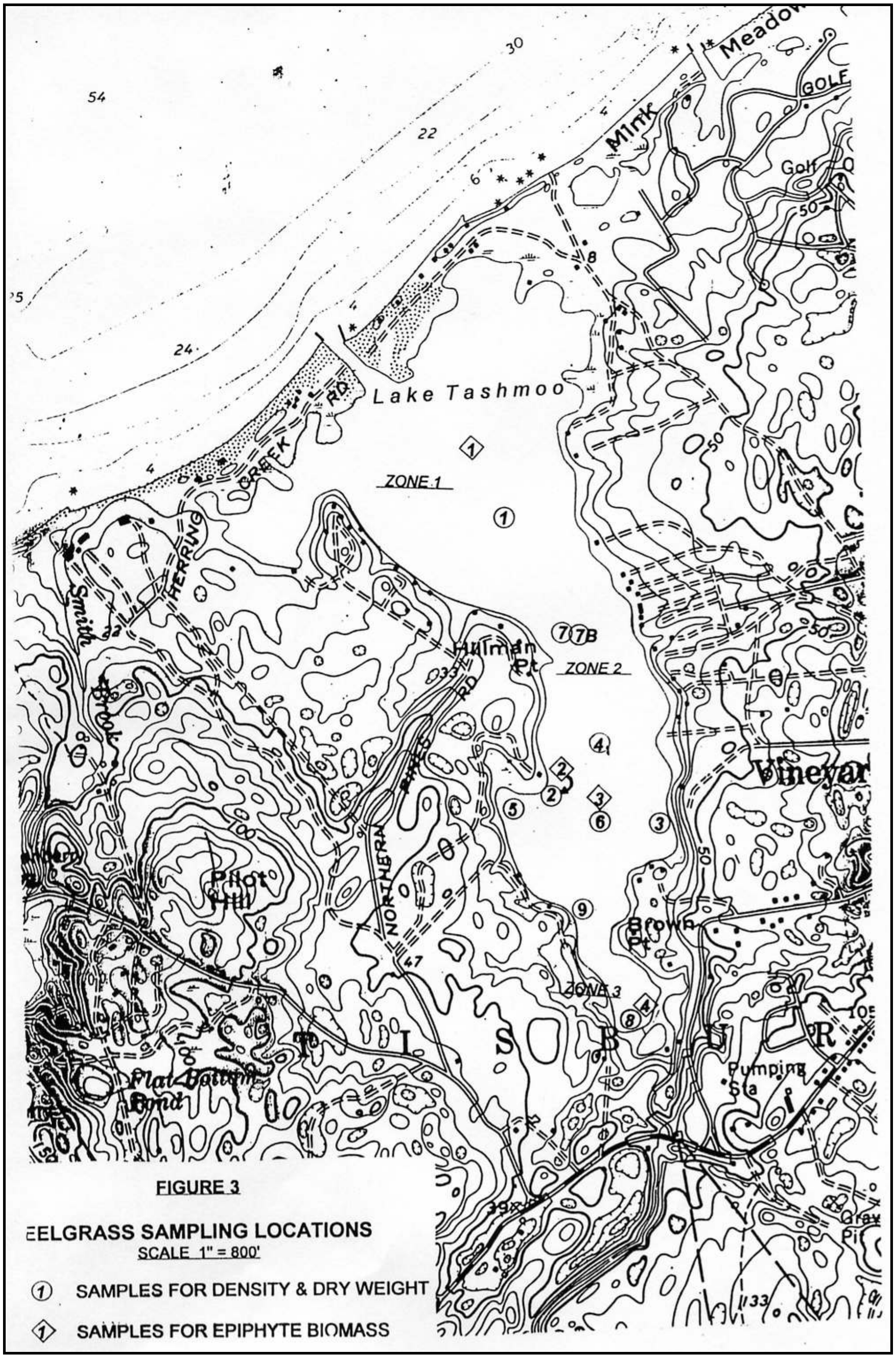

Figure VII-7b. Eelgrass sampling locations by zone (1,2,3) within the Lake Tashmoo System in 1997 (Wilcox and Hempy, 1997). Generally, the most productive areas in terms of stem count and biomass seem to be at the southern end of Zone 1; and in Zone 2 near pier 6 and between piers 15 and 16.

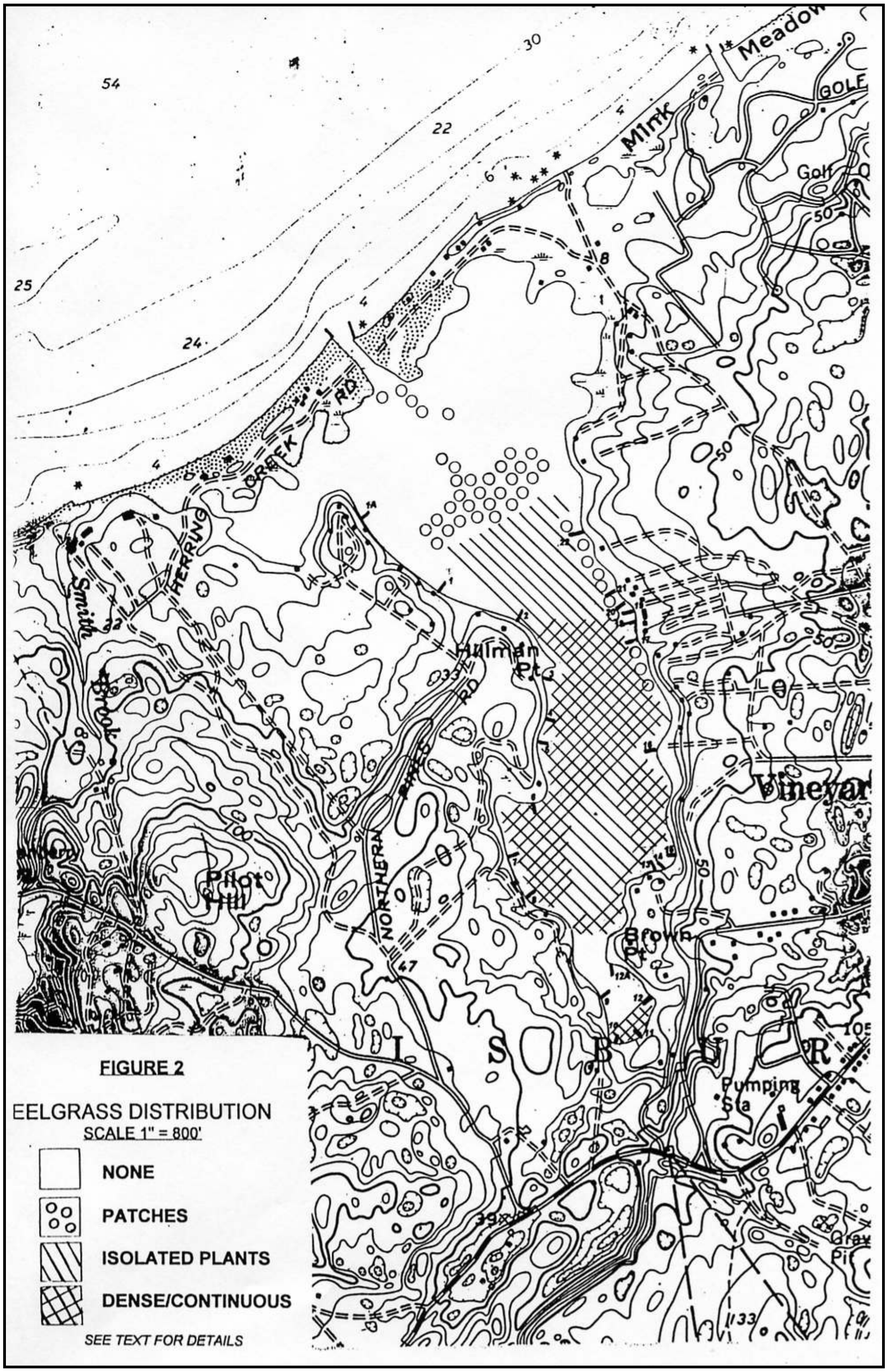

Figure VII-7c. Eelgrass bed distribution within the Lake Tashmoo System in 1997 (Wilcox and Hempy, 1997). Eelgrass areas generally extend the length of the Lake in the 1997 survey consistent with the results of the MassDEP Eelgrass Mapping Program (Figure 7), although they are more discontinuous in the northern portion of the system.

Other factors which influence eelgrass bed loss in embayments can also be at play in the Lake Tashmoo Embayment System, though the recent loss appears completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, however, according to the 1997 MVC eelgrass assessment for Lake Tashmoo, the report indicated that over 130 boats are harbored in Lake Tashmoo during the summer months. Boating pressure may be adding additional stress in nutrient enriched areas that have shown signs of eelgrass, but it does not seem to be the overarching factor as beds persist and beds are lost in areas both with and without moorings. A more specific investigation would be needed to quantify the impact this boating pressure may be excerpting on the existing eelgrass beds, however, that is beyond the scope of the MEP eelgrass analysis and at the discretion of the Town and contingent upon its resources. There have been recent studies on the effectiveness of various mooring designs on limiting eelgrass disturbance. The Town should examine the spectrum of these mooring types as to which is most suited to Tashmoo, should it want to move in that direction. However, by far the largest threat to the health of the eelgrass habitat in Lake Tashmoo is nutrient related and restoration maybe better served by first focusing resources on how to reduce that load from the watershed in order to meet the threshold set through the MEP analysis and then moving toward improved mooring design. While pier construction can cause impacts to eelgrass beds, there are few piers on the shores of Lake Tashmoo and the majority are small structures associated with private homes. It is possible that since the majority of Lake Tashmoo is approved for shell fishing year round, such activity may represent some pressure on the eelgrass resource, particularly for the eelgrass beds that fringe the shoreline.

It is possible to determine quantitative short-term rates of change in eelgrass coverage from the mapping data. Using the 1995 coverage data as the baseline, it appears that a likely eelgrass bed area that might be recovered is on the order of 40 acres if nitrogen management alternatives were implemented (Table VII-3). It is possible that a greater area of eelgrass habitat could be restored, as it is likely that there was more eelgrass present in Lake Tashmoo in 1951. Note that restoration of this eelgrass habitat will necessarily result in restoration of other resources throughout the Lake Tashmoo Embayment System, specifically the infaunal habitat within the margins of the deep basins. However, given the structure of the deep basins, it is not possible to determine the extent to which infauna habitat in the deepest waters will be restored.

Table VII-3. Changes in eelgrass coverage in the Lake Tashmoo Embayment System within the Towns of Tisbury over the past 60 years (MassDEP, C. Costello).

Lake Tashmoo Embayment System: Temporal Change in Eelgrass Coverage						
Embayment	**1951 (acres)**	**1995 (acres)**	**2001 (acres)**	**2006-07 (acres)**	**2010 (acres)**	**Percent Difference (1995 to 2010)**
Lake Tashmoo	114.33	91.17	38.27	37.89	50.16	**45%**

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling for benthic community characterization was conducted at 15 locations throughout the Lake Tashmoo Embayment System (Figure VII-8). At all sites 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,

Figure VII-8. Aerial photograph of the Lake Tashmoo system showing location of benthic infaunal sampling stations (yellow symbol).

anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the significant loss of eelgrass beds, the Lake Tashmoo Estuary is clearly impaired by nutrient overloading. However, to the extent that eelgrass can be restored and that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). In addition, it is necessary to evaluate infauna habitat information relative to the geomorphology of the Lake Tashmoo basins and the periodic weak stratification that increases the potential for impaired habitat (specifically in the uppermost basin of the system south of Brown Point). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

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

Overall, the infauna survey indicated that deeper areas of the system are not supportive of infaunal communities, and that the entire upper basin south of Hilman Point (TMO1 - TMO6, Figure VII-8) is currently supporting few infaunal animals (500-1000 individuals is typical of high quality benthic habitat). In the upper basin (south) the area with a low number of organisms covers a large portion of the entire basin, i.e. the low numbers of organisms is relatively uniform throughout. The low numbers likely indicate seasonal re-colonization of the deep basin where summer-time hypoxia occurs. This was similar to adjacent Lagoon Pond where the deep basins of the entire East Arm averaged < 30 individuals per sample. It should be noted that at these low population levels, Diversity and Evenness are irrelevant, the major finding being the lack of a community.

The lower estuary north of Hilman Point (TMO-7 - TMO 15) is currently supporting high numbers of individuals but distributed among only a moderate number of species ($\leq$10) with a low-moderate species diversity (~2.0). The lower basin is not showing significant habitat impairment as there are few organic enrichment indicators (stress indicators) and species include crustaceans, polychaetes and mollusks, with a prevalence of amphipods in the mid region. These values are indicative of a productive, but moderately impaired habitat.

The chlorophyll-*a* and nitrogen levels of the entirety of Lake Tashmoo are consistent with moderate to high quality habitat in estuaries throughout southeastern Massachusetts. Nitrogen enrichment is moderate at 0.45 mg L^{-1}, 0.36 mg L^{-1} and 0.312 mg L^{-1}, in the upper, mid and lower basins, respectively. Similarly, the average chlorophyll-*a* levels are moderate as well, 6.2 ug L^{-1} and 5.1 ug L^{-1}. As discussed above, it is the extent of periodic summertime oxygen depletion resulting from the periodic reduction in vertical mixing of water column that appears to cause the lack of infauna in the upper deep basin. The effect of the geomorphology of the basins of Lake Tashmoo is an increase in the deposition of organic matter (increasing oxygen uptake from bottom waters) in a system that periodically "isolates" those bottom waters from oxygen rich surface waters for short periods of time (hours to days). The result is periodic hypoxia, in part due to nitrogen enrichment and in part due to "natural" processes. It is certain that the infaunal habitat will improve significantly if the eelgrass habitat is restored in the upper/mid basins through nitrogen management. The relationship of infauna habitat impairment and nitrogen enrichment in the Lake Tashmoo estuary is similar to other estuaries in the region including nearby Lagoon Pond. For example, Uncle Roberts Cove (Lewis Bay) and Ockway Bay (Popponesset Bay) were also found to support depleted benthic communities (37 and <20 individuals/sample, respectively), although a moderate number of species were present. This pattern of moderate diversity, but impoverished numbers is routinely observed in systems with periodic oxygen stress. The benthic habitat data from the Lake Tashmoo estuary was consistent with the levels of total nitrogen (>0.52 mg N L^{-1}, tidally averaged) and chlorophyll a and oxygen depletion in these basins. It should be noted that high quality benthic infaunal habitat, such as in outer Lewis Bay, typically support high numbers of individuals (500-1000 organisms m^{-2}) distributed among a large number of species, 32. The communities are generally composed of a variety of polychaete, crustacean and mollusk species, with high Diversity and Evenness.

Overall, the infaunal habitat quality throughout the basins of the Lake Tashmoo Estuary is consistent with the data collected on levels of dissolved oxygen, chlorophyll, nutrients and organic matter enrichment, as well as basin structure within each component of the system (Table VII-4). Classification of habitat quality necessarily included the structure of the specific estuarine basin, particularly as to whether it was deep or shallow, had stable or unstable sediments (e.g. adjacent barrier beach vs. distant), and its potential for periodic short term stratification due to depth. Based upon this analysis it is clear that the upper basin (south) of Lake Tashmoo is presently showing signs of significant impairment (very poor quality), partially due to depth and basin geomorphology. In contrast the Lower Basin (north) is currently supporting moderately impaired benthic habitat, defined mainly by moderate species numbers (<10) and diversity as well as the patchy dominance by amphipods, *Mediomastus* and *Gemma*. It should be noted that the major restoration target should be eelgrass habitat and that its restoration will necessarily result in a lowering of nitrogen enrichment impacts on the infaunal community throughout the upper and much of the mid basin. (Chapter VIII).

In addition to the benthic infaunal community characterization undertaken during the MEP field data collection program, other biological resources assessments, as developed by the Commonwealth and available to the MEP Technical Team, were integrated into the habitat assessment portion of the MEP nutrient threshold development process. 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 (Figure VII-9) as well as the suitability of a system for the propagation of shellfish (Figure VII-10). Unlike many systems on Cape Cod, the majority of the enclosed waters of the Lake Tashmoo system are approved for the taking of shellfish year round. Only a small portion of the system (head of Lake Tashmoo south of Brown Point) is prohibited for the taking of shellfish year round, indicating the overall system generally supports high bacterial water quality . The major shellfish species with potential habitat within the Lake Tashmoo Estuary are mainly quahogs (*Mercenaria*) and bay scallops throughout the lower to middle portion of the system and extending all the way up to the head of the Lake Tashmoo estuarine reach (Figure VII-8). The map, however, does indicate the lack of potential for shellfish growing within the upper deep channel (light blue area Figure VII-10), which has likely had periodic hypoxia for the past 2 decades and therefore is presently not supportive of shellfish. Such area clearly includes the head of the system south of Brown Point.

Table VII-4. Benthic infaunal community data for the Lagoon Pond embayment system. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m2). Stations refer to map in figure VII-8, replicate samples were collected at each location.

Basin	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)	Stations TMO -
Lake Tashmoo						
Upper Basin (South)	10	53	--[1]	2.55	0.77	1
Upper/Mid Basin (South)	4	35	--[1]	1.55	0.82	2,6
Mid Basin (North)	8	877	6	1.70	0.58	6,7
Lower Basin (North)	11	899	9	2.14	0.62	12,13,15,16

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

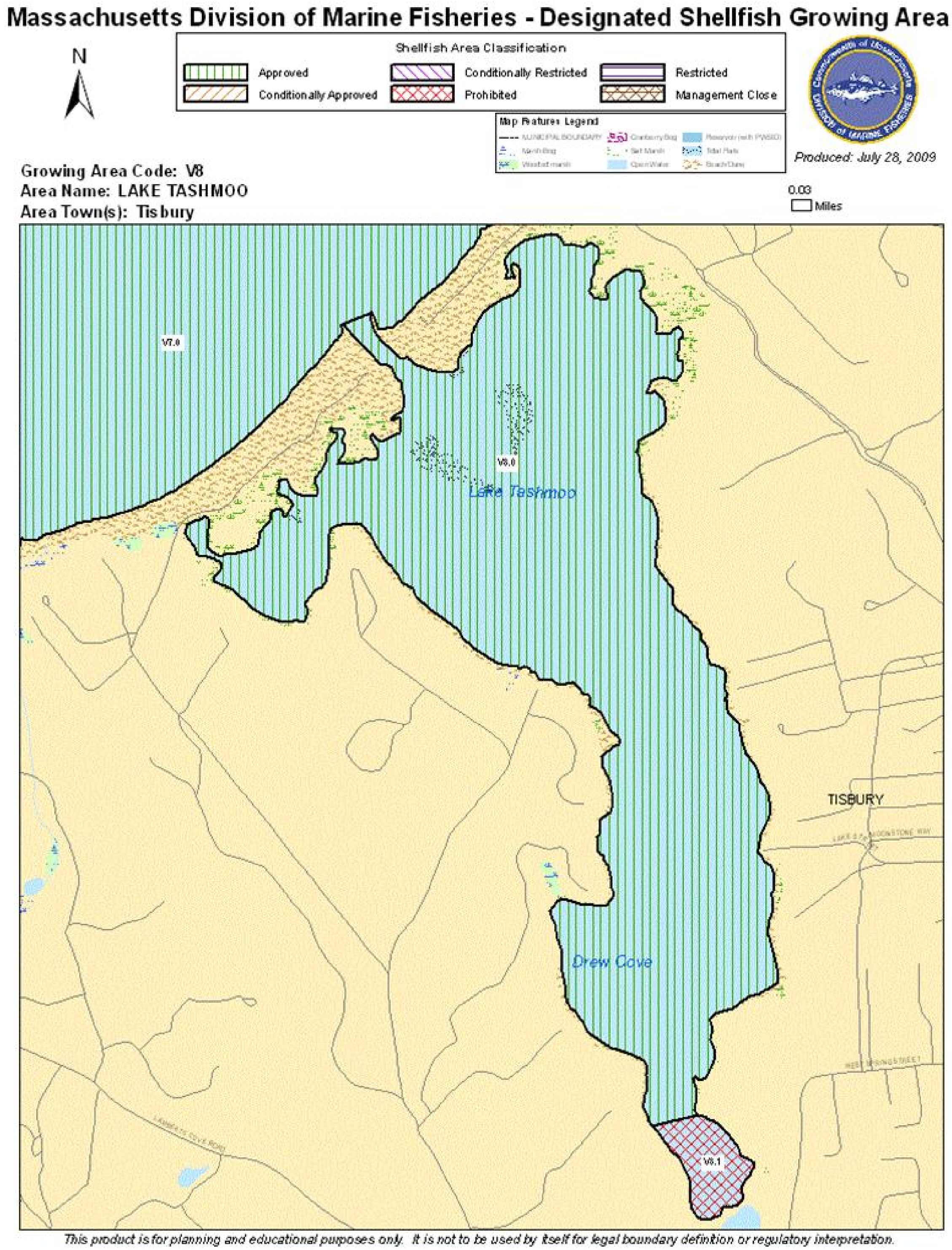

Figure VII-9. Designated shellfish growing areas and status of closures within the Lake Tashmoo system, Town of Tisbury, MA. Source: Massachusetts Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas. The uppermost prohibited basin receives direct freshwater discharge from a small freshwater pond.

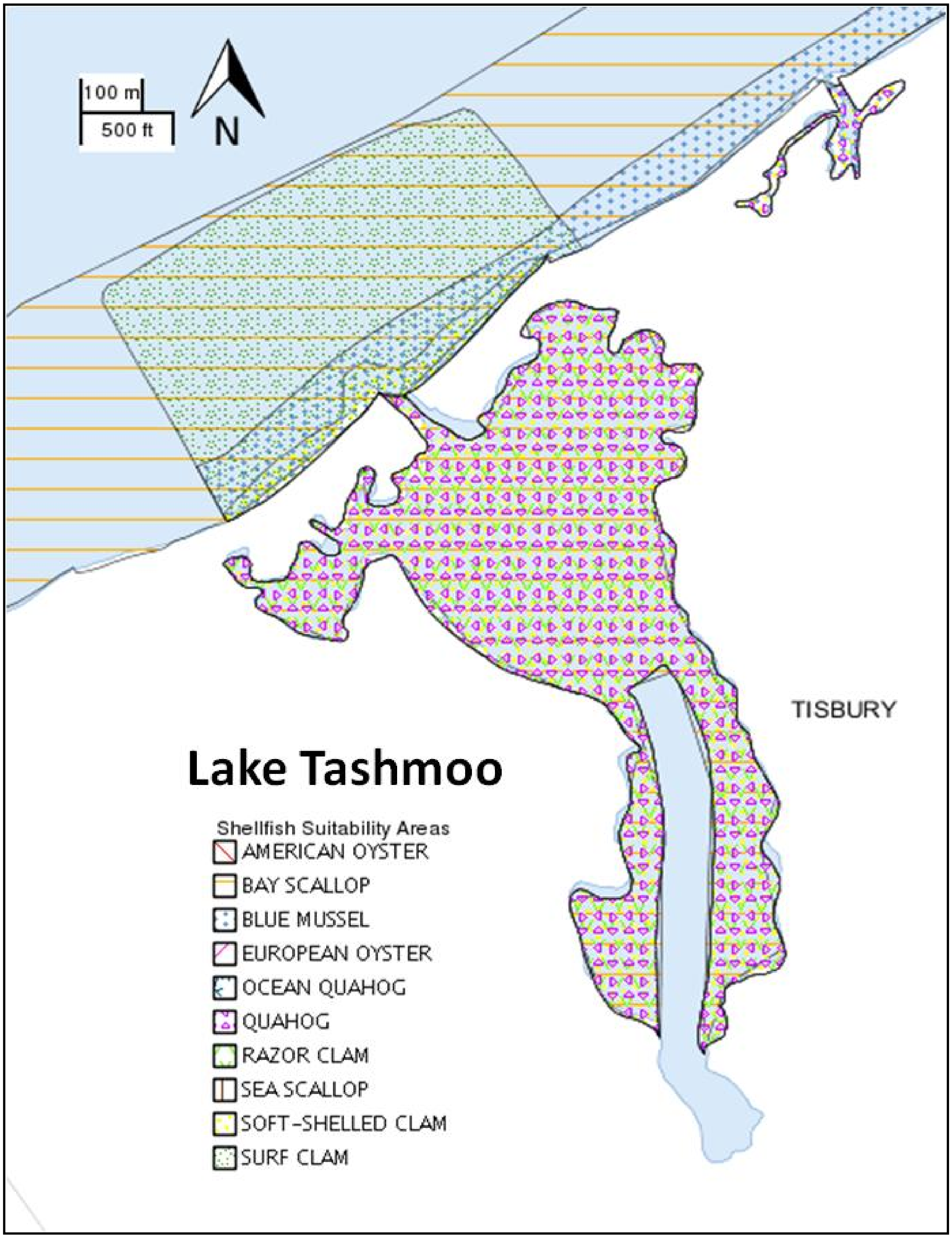

Figure VII-10. Potential shellfish growing areas within the Lake Tashmoo system, Town of Tisbury, MA. Primary species with potential suitable habitat are soft shell clams and quahogs. Note: Suitability does not necessarily mean "presence", for example, the deep basins do not presently support shellfish. Source: Mass GIS.

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll). Additional information on temporal changes within each sub-embayment of an estuary, its associated watershed nitrogen load and geomorphological considerations of basin depth, stratification and functional type further strengthen the analysis. These data were collected to support threshold development for the Lake Tashmoo Estuary by the MEP and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline Water Quality Monitoring Program conducted by the Martha's Vineyard Commission and the Town of Tisbury, with technical and analytical support from the Coastal Systems Program at SMAST-UMass Dartmouth. As part of threshold development an analysis of inorganic N/P molar ratios within the watercolumn of Lake Tashmoo was conducted to confirm that nitrogen is the nutrient to be managed (i.e. is the eutrophying nutrient). The ratio in Lake Tashmoo (all monitoring stations) ranged from 2.3 mg N L^{-1} to 4.3 mg N L^{-1}, clearly below the Redfield Ratio value (16), indicating that nitrogen addition is the nutrient increasing phytoplankton production in this estuary and therefore is the nutrient to be managed to restore the observed impairments.

Lake Tashmoo is a simple estuary formed as a composite of drowning a valley (upper reaches) and a lagoon forming the lower reach, due to the development of a barrier beach across the entrance. It is composed of a single functional type of basin: open water embayment with multiple deep basins (4-5 meters depth) that periodically develop weak salinity stratification (1-2 ppt) and bottom water oxygen depletion. There is a single freshwater inflow via the herring ladder to the headwaters of the upper estuarine basin. In general, each type of functional component (salt marsh basin, embayment, tidal river, deep basin {sometimes drown kettles}, shallow basin, etc.) of an estuary has a different natural sensitivity to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of the specific type of basin and the ability to support eelgrass beds and the types of infaunal communities that they support. At present, the Lake Tashmoo Estuary is showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Chapter VII), indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

Overall, the estuary is currently showing some nitrogen related habitat impairment throughout its tidal reach. The upper basin and lower basin are relatively deep for southeastern Massachusetts estuaries on Vineyard Sound and Buzzards Bay. This structure allows periodic weak salinity stratification (weak vertical mixing), which makes these basins sensitive to the negative effects of nitrogen enrichment. The result is periodic hypoxia in the upper basin and oxygen depletion in the lower basin as a result of in situ phytoplankton production and deposition. In addition, the increased phytoplankton biomass decreases light penetration to the bottom colonizing eelgrass adding further stress and accelerating bed loss. It is almost certain that the observed periodic hypoxia in the uppermost headwater basin resulted in the loss of the beds observed in 2001 from the 1995 and 1997 coverage. The pattern of loss is consistent with nitrogen enrichment, following the gradient of increasing nitrogen and chlorophyll-*a* levels from the inlet to the head waters. The decline in eelgrass within these basins makes restoration of eelgrass the target for TMDL development by MassDEP and the primary focus of threshold development for these areas for the MEP. It should be noted that the lagoon formed behind the barrier beach has not historically supported stable eelgrass beds. It appears that the unstable sands and growing flood tidal delta do not support eelgrass beds in this region. This is supported by the observation that the 1951 eelgrass beds and the new beds in the inlet channel appear to abut this delta but not colonize it.

In addition, at present the infaunal communities are also moderately impaired in the lower basin, but habitat is significantly impaired to degraded throughout the upper basin as seen by the low numbers of organisms (<50 org m^{-2}). However, given the level of impairment and the location of this basin within the Lake Tashmoo Estuary, it is certain that restoring eelgrass habitat within the upper and mid-lower basins will result in restoration of the infaunal habitat in the lower portion of the system, as nitrogen enrichment will be significantly reduced throughout the overall estuary (Section VIII.3).

Eelgrass: At present, eelgrass beds exist mainly within the mid-upper basin of the Lake Tashmoo Estuary with smaller beds in the lower portion of the system closest to the inlet. In 1951 eelgrass coverage extended throughout the main basin of the estuary from just upgradient of Kuffies Point to the uppermost tidal reach near the discharge from the freshwater pond at the present herring ladder covering ~114 acres. However, both the 1995 MassDEP and 1997 MVC surveys indicate that eelgrass coverage had been lost in the uppermost reach and certainly from the lower portion of the main basin, primarily the deeper waters, but coverage was still significant at ~90 acres. This trend continued to 2001 with additional loss at the lower and upper margins of the main basin beds further reducing coverage to 38 acres, again with loss mainly from deep waters. The coverage has remained relatively constant to 2010, with losses from the upper basin being more than offset by development of a new bed within the channel to the tidal inlet in the lower portion of the estuary, where water depth is shallow and water quality is maintained at a high level by incoming water from Vineyard Sound (Figure VII-7b). It appears that eelgrass is generally present at depths less than 2.5-3.0 meters, consistent with observed light penetration data from the water quality monitoring program (average Secchi depths of ~2.1 m).

Overall, the observations are diagnostic of a moderate level of nitrogen enrichment, where eelgrass coverage is being reduced over decades in the uppermost tidal basin with elevated average field nitrogen levels of 0.45 mg L^{-1}, levels found in areas that have lost eelgrass in virtually all of the estuaries assessed by the MEP to date. In addition, the eelgrass loss from the deep waters at lower levels of nitrogen enrichment are consistent with observations where lower nitrogen thresholds are required to lower phytoplankton shading of eelgrass beds to allow their persistence at depth within southeastern Massachusetts estuaries. Further, the observation that loss of coverage is relatively recent and that significant eelgrass coverage still exists indicates that this estuary has exceeded nitrogen threshold to support eelgrass, but only by a moderate amount of nitrogen enrichment.

Analysis of nitrogen levels and eelgrass decline indicate that in the uppermost basin of Lake Tashmoo where eelgrass has been lost, average total nitrogen (TN) from the multi-year Water Quality Monitoring Program were relatively high, 0.45 mg L^{-1}. The absence of eelgrass in this basin is consistent with loss of coverage in Lagoon Pond at nitrogen levels observed by the monitoring program of 0.39 mg N L^{-1}. In contrast, eelgrass in Lake Tashmoo appears to support relatively stable beds in the upper/mid basin at a TN level of 0.36 mg N L^{-1} (MV4). At slightly higher nitrogen levels at the uppermost edge of the 1995 eelgrass coverage where eelgrass has been subsequently lost, TN was found to currently be 0.386 mg N L^{-1} (water quality model, Chapter VI). So it appears that habitat restoration must lower TN level to less than 0.386 mg N L^{-1} within the channel adjacent Brown Point to restore eelgrass lost between 1995 and 2001.

Similar levels of nitrogen and eelgrass loss/persistence were observed in adjacent Lagoon Pond, which is also showing a continuing estuary-wide decline in eelgrass coverage with losses of beds from the upper basin and from the deeper waters. This pattern of bed loss, where beds appear to retreat from the upper basins toward the inlet and from the deeper to shallower water, is diagnostic of nitrogen enrichment effects in southeastern Massachusetts estuaries. Previous MEP assessments of Cape Cod estuaries indicate that the sensitivity of eelgrass to nitrogen enrichment affects is directly related to water depth. Eelgrass beds in very shallow water (1 meter) are able to tolerate higher nitrogen and chlorophyll-*a* levels and lower light penetration than eelgrass in deeper systems (2-3 meters). This appears to be the case for both Lake Tashmoo and Lagoon Pond, as well.

The similar structure and level of nitrogen enrichment in Lagoon Pond results in a similar pattern of eelgrass loss as that observed in Lake Tashmoo. The absence of eelgrass within the West Arm of Lagoon Pond and near loss of eelgrass from the upper basin of the East Arm are associated with tidally averaged nitrogen (total nitrogen, TN) levels of 0.378 mg N L^{-1} and 0.385 mg N L^{-1}, respectively, nearly identical to TN levels in the area of loss in the Brown Point channel of Lake Tashmoo (0.386 mg N L^{-1}). In addition, stable eelgrass beds were observed within the lower basin of Lagoon Pond at tidally averaged nitrogen levels of 0.328 mg N L^{-1}, with fringing beds persisting in the shallow margins of the upper and mid basin at nitrogen levels between 0.371 mg N L^{-1} and 0.338 mg N L^{-1}. Also, in Waquoit Bay at similar depths, eelgrass was found to be slowly declining at average TN concentrations of 0.395 mg L^{-1} (lower basin of Waquoit Bay). In West Falmouth Harbor eelgrass declined when nitrogen enrichment resulted in levels over 0.35 mg L^{-1}. These levels of enrichment are similar to those found in the present assessment of Lake Tashmoo.

Based upon the above analysis, eelgrass habitat was selected as the primary nitrogen management goal for the Lake Tashmoo Estuary, with parallel restoration of infaunal habitat occurring as management alternatives are implemented for eelgrass. It is not possible to determine the maximum amount of eelgrass habitat that can be restored, as the quantitative surveys only began in 1995. However, using the 1995 coverage data as the baseline, it appears that a minimum eelgrass bed area on the order of 113 acres should be recovered if nitrogen management alternatives are implemented (Table VII-3). It is possible that a greater area of eelgrass habitat may be restored, to the extent that there was more eelgrass present in Lake Tashmoo prior to 1995. It does appear that the 91.17 acres is a good approximation, as the 1987 and 1995 surveys generally show the same eelgrass beds. Note that restoration of this eelgrass habitat will necessarily result in restoration of other resources throughout the Lake Tashmoo Embayment System, specifically the shallower eelgrass habitat in the shallow waters along the east and particularly the west shore of the mid and lower basins of the system and the infaunal habitat within the margins of the deep basins. However, given the structure of the deep basins, it is not possible to determine the extent to which infauna habitat in the deepest waters will be restored. These goals are the focus of the MEP threshold analysis presented in Section VIII-3.

As eelgrass within Lake Tashmoo is a critical habitat structuring the productivity and resource quality of the entire system, and is presently showing impairment, restoration of this resource is the primary target for overall restoration of this critical estuarine system. The persistence of beds in the mid basin suggests that nitrogen enrichment is moderate and that the system is just over its nitrogen threshold, which is also consistent with the observed chlorophyll-

a levels. However, the losses of bed area from 1995-2006 indicate that nitrogen enrichment is continuing. As the loss of eelgrass in these areas is well documented and consistent with nitrogen enrichment, re-establishing these beds (referring to areas where there was eelgrass documented during the period 1995-2006 that were not present when the 2010 survey was completed) should be the target for restoration as this habitat would be recovered with appropriate nitrogen management. In contrast, since there is little evidence of the lowermost portion of the estuary behind the barrier beach ever having had eelgrass habitat, most likely due to unstable sediments and sand transport associated with the flood tidal delta. Establishment of eelgrass in this lower region cannot be supported as a specific restoration goal

It should be noted that restoration of the eelgrass habitat in appropriate areas of the Lake Tashmoo system will necessarily result in restoration of other resources throughout the Lake Tashmoo Estuary, specifically the infaunal habitat within the lower and upper shallow water areas and to a lesser extent the upper most deep basin. These goals are the focus of the MEP threshold analysis presented in Section VIII-3.

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

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate conditions of poor habitat quality within the deep basin waters (>3 meters) of Lake Tashmoo under moderately nutrient enriched conditions. The chlorophyll-*a* levels also indicate only moderate nitrogen enrichment, while the bottom water oxygen levels show periodic hypoxia in the upper basin and moderate oxygen depletion in the lower basin. It appears that the basins which constitute much of the bottom habitat of Lake Tashmoo are periodically not vertically well mixed during the summer, which allows the moderate level of nutrient enrichment to occasionally produce very low oxygen conditions. The oxygen data is consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-*a* coupled with periods of reduced vertical mixing within the basins. The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follows the spatial pattern of total nitrogen levels in this system. It is clear that Lake Tashmoo's nutrient enrichment response is magnified by its basin structure combined with the depositional nature of the basins (as evidenced by the accumulations of drift macroalgae) and periodic reduced vertical mixing. The result is poor quality benthic animal habitat within the deeper waters of the upper basin. It should be noted that the periods of reduced vertical mixing result from weak salinity stratification, where surface waters are only ~1-2 ppt "fresher" than bottom waters. It appears that these periods are brief as no evidence of a vertical nitrogen gradient was evident in the water quality monitoring results.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate conditions of moderate habitat quality at the Hillman Point mooring location and moderate to poor habitat quality at the Brown Point DO recording site respectively (Figures VII-3 through VII-6). The chlorophyll-*a* levels indicate only moderate nitrogen enrichment, while the bottom water oxygen levels show periodic hypoxia at the upper pond location. It is likely that the effects of nitrogen enrichment (0.45 mg/L) on oxygen levels in the upper basins is enhanced by periodic short-term stratification in the deep waters of the upper basin. The oxygen data are consistent with organic matter enrichment, primarily from phytoplankton production which shows blooms to 10-20 mg/L (Water Quality Monitoring

Program). The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follow the spatial pattern of total nitrogen levels in this system (Chapter VI) and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuary. However, it is clear that nutrient enrichment response in Lake Tashmoo Pond is magnified by its basin structure, which when combined with the depositional nature of the upper basin (head water to Hillman Point) and accumulations of macroalgae, results in poor quality and benthic animal habitat within the deeper water of the upper basin (TMO1-TMO6, 3.15 meters total depth), see Section VII-4. The loss of eelgrass in the uppermost tidal reach is almost certainly a result of its depth and depositional nature (unconsolidated fluid muds).

Measured dissolved oxygen depletion indicates that the southern (upper) region of Lake Tashmoo shows high levels of oxygen stress whereas the northern (lower) region shows low to moderate levels of oxygen stress. This is seen clearly in the data record collected from the autonomous oxygen recorders deployed in the upper and mid pond regions (Figure VII-2). 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. The pattern of oxygen depletion, levels of chlorophyll-*a* and nitrogen are consistent with the observed pattern of eelgrass loss (Section VII.3). Moreover, the pattern of temporal loss is consistent with an estuarine system that is just beyond its ability to assimilate nitrogen loads without impairment. Similarly, infaunal habitats (Section VII.4) also appear to be impaired by organic matter enrichment resulting from nitrogen loading, with the level of habitat impairment being greater in deep versus shallow water. Management of nitrogen levels through reductions in watershed nitrogen inputs are required for restoration of eelgrass and infaunal habitats within the Lake Tashmoo Estuary. It is important to note, maintaining proper flushing of Lake Tashmoo in concert with reducing nitrogen loads from the watershed is aimed at reducing phytoplankton growth (due to nitrogen fertilization of phytoplankton) and organic matter deposition to the sediments. It is the elevated plant growth and subsequent decay that are the major cause of the periodic low oxygen events. This has been observed throughout the world's nutrient enriched estuaries, including those on Martha's Vineyard and Cape Cod. Lowering the nitrogen levels in the estuary, through flushing enhancements or source reduction, lowers the amount of organic matter production and subsequent decay resulting in improved oxygen conditions, reversing the nutrient related habitat impairment observed by the MEP.

Infaunal Communities: In all areas and particularly those that do not support eelgrass beds, benthic animal indicators are used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The survey of infauna communities throughout Lake Tashmoo indicated a system presently supporting impaired benthic infaunal habitat throughout its basins, with the upper basin showing significant impairment and the lower basin moderate impairment. The pattern of impairment follows the depth and the hypoxia, macroalgal accumulations and higher phytoplankton biomass in the upper basin and the moderate oxygen depletion, absence of macroalgae and moderate phytoplankton biomass in the lower basin.

The loss of the deep basin infauna habitat results from the observed periodic reduction in vertical mixing by the weak salinity stratification of waters in these deep basins. The effect of the geomorphology of Lake Tashmoo's basins is to increase deposition of organic matter (increasing oxygen uptake from bottom waters) is a system that "isolates" those bottom waters from oxygen rich surface waters for short periods of time (hours to days). The result is periodic hypoxia and anoxia, in part due to nitrogen enrichment and in part due to "natural" processes.

Overall, the infauna survey indicated that deeper areas (>3 meters of the upper basin) are not supportive of infaunal communities and that the entire upper basin south of Hillman Point (TMO1 - TMO6, Figure VII-8) is currently supporting few infaunal animals. In the upper basin (south) the area with low numbers of organisms covers a large portion of the entire basin. The low numbers likely indicate seasonal re-colonization of the deep basin where summer-time hypoxia occurs. This was similar to adjacent Lagoon Pond system where the deep basins of the entire East Arm averaged < 30 individuals per sample. It should be noted that at these low population levels, Diversity and Evenness are irrelevant, the major finding being the lack of a community.

The lower estuary north of Hillman Point (TMO-7 - TMO 15) is currently supporting high numbers of individuals but distributed among only a moderate number of species ($\leq$10) with a low-moderate species diversity (~2.0). The lower basin is not showing significant nitrogen related habitat impairment as there are few organic enrichment indicators (stress indicators) and species include crustaceans, polychaetes and molluscs, with a prevalence of amphipods in the mid region. These values are indicative of a productive, but moderately impaired habitat.

The chlorophyll-*a* and nitrogen levels across the entirety of Lake Tashmoo are consistent with moderate to high quality habitat in estuaries throughout southeastern Massachusetts. Nitrogen enrichment is moderate, 0.45 mg L^{-1}, 0.36 mg L^{-1} and 0.312 mg L^{-1}, in the upper, mid and lower basins, respectively, as are the average chlorophyll-*a* levels, 6.2 ug L^{-1} and 5.1 ug L^{-1}. As discussed above, it is the extent of periodic summertime oxygen depletion resulting from the periodic reduction in vertical mixing of water column (salinity stratification 1-2 ppt) that appears to cause the lack of infauna in the upper deep basin. The effect of the geomorphology of the basins of Lake Tashmoo is an increase in the deposition of organic matter (increasing oxygen uptake from bottom waters) in a system that periodically "isolates" those bottom waters from oxygen rich surface waters for short periods of time (hours to days). The result is the observed periodic hypoxia, in part due to nitrogen enrichment magnified by basin structure. It is certain that the infaunal habitat will improve significantly if the eelgrass habitat is restored in the upper/mid basins through nitrogen management.

The relationship of infauna habitat impairment and nitrogen enrichment in the Lake Tashmoo estuary is similar to other estuaries in the region, including nearby Lagoon Pond. For example, Uncle Roberts Cove (Lewis Bay) and Ockway Bay (Popponesset Bay) were also found to support depleted benthic communities (37 and <20 individuals/sample, respectively), although a moderate number of species were present. This pattern of moderate diversity, but impoverished numbers is routinely observed in systems with periodic oxygen stress. The benthic habitat data was consistent with the levels of total nitrogen (>0.52 mg N L^{-1}, tidally averaged) and chlorophyll-*a* and oxygen depletion in these basins.

It should be noted that high quality benthic infaunal habitat, such as in outer Lewis Bay, typically support high numbers of individuals (500-1000 organisms m^{-2}) distributed among a large number of species, 25-32. The communities are generally composed of a variety of polychaete, crustacean and mollusk species, with high diversity and Evenness.

Overall, the infaunal habitat quality throughout the basins of the Lake Tashmoo Estuary is consistent with the data collected on dissolved oxygen, chlorophyll-*a*, nutrients, organic matter enrichment and basin structure within each component of the system (Table VIII-1). Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to whether it was deep or shallow, had stable or unstable sediments (e.g. adjacent barrier beach vs. distant), and its potential for stratification due to depth. Based upon this analysis it is clear that the upper basin (south) of Lake Tashmoo is presently supporting infauna animal habitat that is significantly impaired as seen in its low total organism numbers (poor quality), partially due to depth and basin geomorphology. In contrast the Lower Basin (north) is currently supporting moderately impaired benthic habitat, defined mainly by its high numbers of total organisms, moderate species numbers (<10) and diversity as well as the patchy dominance by amphipods, *Mediomastus* and *Gemma*. It should be noted that the major restoration target for Lake Tashmoo should be eelgrass habitat and that its restoration will necessarily result in a lowering of nitrogen enrichment impacts on the infaunal community throughout the upper and much of the mid basin. (Chapter VIII).

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

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

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

At present, the Lake Tashmoo Estuary is showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats, indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system. The upper basin and lower basin are relatively deep and this structure allows periodic weak salinity stratification (weak vertical mixing), which makes these basins sensitive to the negative effects of nitrogen enrichment. The result is periodic hypoxia in the upper basin and oxygen depletion in the lower basin as a result of in situ phytoplankton production and deposition. In addition, the increased phytoplankton biomass decreases light penetration to the bottom colonizing eelgrass adding further stress and accelerating bed loss. It is almost certain that that the observed periodic hypoxia in the uppermost headwater basin resulted in the loss of the beds observed between 1995 and 2001. The pattern of loss is consistent with nitrogen enrichment, following the gradient of increasing nitrogen and chlorophyll a levels from the inlet to the headwaters.

Table VIII-1. Summary of nutrient related habitat quality throughout the Lake Tashmoo Estuary, Towns of Tisbury, West Tisbury and Oak Bluffs, MA, based upon assessments in Section VII. The Lower main basin (North) extends from the inlet to Hillman Pt. and consists of sand accumulations and a deep central channel (3 m), while the Upper Basin (South) is deep (3 m) and includes Drew Cove and extends to the uppermost tidal reach. WQM indicates: the Lake Tashmoo Water Quality Monitoring Program (2001-2007).

Health Indicator	Lake Tashmoo Estuary	
	Upper Basin (South)	Lower Basin (North)
Dissolved Oxygen	SI[1]	MI[2]
Chlorophyll	MI[3]	H/MI[4]
Macroalgae	MI[5]	MI[6]
Eelgrass	MI/SI[7]	MI[8]
Infaunal Animals	SD[9]	MI[10]
Overall:	**MI/SI[11]**	**MI[12]**

1 – oxygen depletion at mooring shows periodic hypoxia (< 2mg/L) frequently <4 mg/L and < 3mg/L, 30% of record, WQM minima of 3.8 mg/L. in area of mooring.
2 – oxygen depletion at mooring typically >5 mg/L 87% of record and always >4 mg/L. DO consistent with WQM which showed grab sample DO minima 5.4-5.9 in area of mooring.
3 – moderate summer chlorophyll levels generally <10 ug/L (92% of time), averaging 6.2 ug/L, maximum 15 ug/L. WQM average in summer (2002-2007) was 9.3 ug/L, maximum 20 ug/L.
4 – low to moderate summer chlorophyll levels <5 ug/L, 60% and <10 ug/L 94% of record, averaging 5.1 ug/L, maximum 13 ug/L. WQM summer mean (2002-2007)= 3.9-4.3 ug/L, maximum 7.6-9.8 ug/L.
5 – patches of dense drift *Gracillaria*, deposited in deep basin, (south basin has patches of algal mat)
6 – patches of sparse *Gracillaria*, sparse attached *Codium*.
7 – MassDEP (C. Costello) indicates that eelgrass coverage significantly declined 1951-1995, 1995-2001. However, still dense coverage in some areas. Loss is mainly in deeper waters (lower light penetration). MVC 1997 survey consistent with MassDEP 1995 survey.
8 – MassDEP (C. Costello) indicates loss from uppermost margins of coverage with loss of dense beds. in shallower water where periodic hypoxia and blooms were observed. But significant coverage still observed in 2010.
9 – low numbers of individuals (<30-50 per sample) and low number of species, habitat not presently supporting an infaunal animal community throughout the deep basin.
10 – high numbers of individuals and moderate diversity (1.70-2.14), low-moderate species numbers (8-11) and Eveness (0.6), but with very few stress indicator species. Community dominated by polychaetes, crustaceans, and mollusks, with some amphipods. Indicative of moderate organic enrichment.
11 – Moderate-Significant Impairment: primarily due to reduction in eelgrass bed coverage (1995-2001) but persistence of some eelgrass beds, periodic D.O. depletion (hypoxia) and significantly degraded animal community habitat, moderate chlorophyll levels and moderate accumulation of drift macroalgae.
12 – Moderate Impairment: primarily due to the loss of eelgrass from the deeper waters but persistence of some dense eelgrass beds, low species numbers and diversity of benthic community but with high numbers and low numbers of stress indicator species, consistent with moderate summer depletion in D.O, low summer chlorophyll levels and low-moderate accumulation of drift macroalgae. Eelgrass and infaunal habitat impairments form the major basis of the assessment.

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

The observed loss of eelgrass coverage is diagnostic of a moderate level of nitrogen enrichment, where eelgrass coverage is being reduced over decades in the uppermost tidal basin with an elevated average field nitrogen level of 0.45 mg L^{-1}. This level is associated with lost eelgrass habitat in virtually all of the estuaries in southeast Massachusetts. In addition the eelgrass loss from the deep waters at lower levels of nitrogen enrichment are consistent with observations where lower nitrogen thresholds are required to lower phytoplankton shading of eelgrass beds to allow their persistence. Further, the observation that loss of coverage is relatively recent and that significant eelgrass coverage still exists indicates that this estuary has only recently exceeded its nitrogen threshold to support eelgrass and only a moderate reduction in loading may be required for restoration.

Analysis of nitrogen levels and eelgrass decline indicate that in the uppermost basin of Lake Tashmoo where eelgrass has been lost, average total nitrogen (TN) from the multi-year Water Quality Monitoring Program was relatively high, 0.45 mg L^{-1}. The present absence of eelgrass from the uppermost basin where it occurred in 1951 and 1995 is consistent with loss of coverage in Lagoon Pond at nitrogen levels of 0.39 mg N L^{-1}. In contrast, eelgrass habitat in Lake Tashmoo appears to be comprised of relatively stable beds in the upper/mid basin area of the system at a TN level of 0.36 mg N L^{-1} (MV4). Eelgrass persists within the deep upper basin at this TN level. At slightly higher nitrogen levels at the uppermost edge of the 1995 eelgrass coverage, where eelgrass has been subsequently lost, tidally averaged TN was slightly higher, 0.386 mg N L^{-1} (water quality model, Chapter VI). So it appears that habitat restoration must lower TN level in the upper basin to less than 0.386 mg N L^{-1}, but not lower than 0.36 mg N L^{-1}.

These levels of nitrogen and eelgrass loss/persistence were observed in adjacent Lagoon Pond, which is also showing a continuing estuary-wide decline in eelgrass coverage with losses of beds from the upper basin and from the deeper waters. The absence of eelgrass within the West Arm of Lagoon Pond and near loss of eelgrass from the upper basin of the East Arm are associated with tidally averaged nitrogen (total nitrogen, TN) levels of 0.378 mg N L^{-1} and 0.385 mg N L^{-1}, respectively, nearly identical to TN levels in the area of loss in the Brown Point channel in Lake Tashmoo (0.386 mg N L^{-1}). In addition, stable eelgrass beds were observed within the lower basin of Lagoon Pond at tidally averaged nitrogen levels of 0.328 mg N L^{-1}. Also, in Waquoit Bay at similar depths, eelgrass was found to slowly decline at average TN concentrations of 0.395 mg L^{-1} (lower basin of Waquoit Bay) and in West Falmouth Harbor eelgrass declined when nitrogen enrichment resulted in levels over 0.35 mg L^{-1}.

Based upon the above analysis and to meet the stated criteria for a Sentinel Station, the most appropriate placement of the Sentinel Station is at the uppermost edge of the 1995 eelgrass coverage in the southern basin (note the 1997 survey showed a patch even further south in shallow water). The station must be in the channel adjacent Browning Point. Unfortunately, the Water Quality Monitoring Station is further south (MV5) is a region of mixing and steep gradients in salinity and nitrogen due to the focused watershed inflows. Fortunately, the MEP Water Quality Model provides tidally averaged TN within the Brown Point Channel, which is currently 0.386 mg N L^{-1} (station location, see below). Lowering nitrogen at this upper station will result in a lowering of nitrogen levels throughout the down gradient estuary, restoring other areas of eelgrass loss and improving benthic animal habitats.

From multiple lines of evidence presented in the existing assessment it appears that the threshold for stable eelgrass habitat in Lake Tashmoo must be less than 0.386 mg N L^{-1}, as this is the present level and loss is continuing. Similarly, it appears that eelgrass beds presently extant in adjacent Lagoon Pond at nitrogen levels of 0.371 mg N L^{-1} continue to show some loss. Similarly eelgrass loss in Waquoit Bay has been documented at 0.395 mg L^{-1} (lower basin of Waquoit Bay) and in West Falmouth Harbor eelgrass declined when nitrogen enrichment reached levels over 0.35 mg L^{-1}. All of these systems have deep water habitat. Based upon these observations and those from other systems, a tidally averaged nitrogen threshold for Lake Tashmoo of 0.36 mg N L^{-1} will allow restoration of areas of impaired eelgrass habitat. Additionally, this TN level is currently supportive of stable eelgrass habitat within the upper basin of Lake Tashmoo. This threshold is only slightly higher than that for the slightly shallower basins (2-3 m) of West Falmouth Harbor and Phinneys Harbor (0.35 mg N L^{-1}) to account for the increased depth in Lake Tashmoo. In addition, lowering the level of nitrogen enrichment at the sentinel station will lower nitrogen levels throughout the estuary (Section VIII.3) with the parallel effect of improving infaunal habitats throughout the estuary. Therefore, the goal to achieve the nitrogen target at the sentinel location and restore the historical eelgrass habitat within Lake Tashmoo also results in the restoration of infaunal habitat within the shallow sediments throughout the system and addresses the impairments in the infauna habitat within the deep basins. The nitrogen loads associated with the threshold concentration at the sentinel location are discussed in Section VIII.3, below.

VIII.3 DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Lake Tashmoo system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for Lake Tashmoo. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment. A comparison between present septic and total watershed loading and the loadings for the two modeled threshold scenarios is provided in Tables VIII-2 and VIII-3.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required more than 40% removal of septic load (associated with direct groundwater discharge to the embayment) for the entire system. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. For example, removal of 50% of the septic load from the main Lake Tashmoo watershed results in a 39% reduction in total watershed nitrogen load for the same main watershed. No load reduction was necessary for the Upper Tashmoo watershed. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent ‘worst-case’ summertime conditions. The benthic flux for this modeling effort is reduced from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Buzzards Bay, as discussed in Section VI.2.6.1.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN concentrations of typically greater than 30% is required in the system, between the main harbor basin (between Hillman Point and Brown Point) and the herring run discharging from the freshwater spring at the head of Lake Tashmoo.

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

The basis for the watershed nitrogen removal strategy utilized to achieve the system threshold may have merit, since this example of a nitrogen remediation approach is focused on watersheds where groundwater is flowing directly into the estuary. Future nitrogen management should take advantage of natural nitrogen attenuation, where possible, to ensure the most cost-effective nitrogen reduction strategies. However, “planned” use of natural systems has to be done carefully and with the full analysis to ensure that degradation of these systems will not occur. One clear finding of the MEP has been the need for analysis of the potential associated with restored wetlands or ecologically engineered ponds/wetlands to enhance nitrogen attenuation. Attenuation by ponds in agricultural systems has also been found to work in some cranberry bog systems, as well. Cranberry bogs, other freshwater wetland resources, and freshwater ponds provide opportunities for enhancing natural attenuation of their nitrogen loads. Restoration or enhancement of wetlands and ponds associated with the lower ends of rivers and/or streams discharging to estuaries are seen as providing a dual service of lowering infrastructure costs associated with wastewater management and increasing aquatic resources associated within the watershed and upper estuarine reaches.

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Lake Tashmoo – main basin	15.416	7.708	-50.0%
Drew Cove	2.885	2.596	-10.0%
Lake Tashmoo - upper	0.496	0.496	+0.0%
System Total	18.797	10.801	-42.5%

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Lake Tashmoo – main basin	19.907	12.199	-38.7%
Drew Cove	4.433	4.144	-6.5%
Lake Tashmoo - upper	0.764	0.764	+0.0%
System Total	25.104	17.107	-31.9%

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Lake Tashmoo – main basin	12.199	3.304	7.792
Drew Cove	4.144	0.504	6.837
Lake Tashmoo - upper	0.764	-	-
System Total	17.107	3.808	14.630

Table VIII-5. Comparison of model average total N concentrations from present loading and the **threshold scenario**, with percent change over background in Vineyard Sound (0.270 mg/L), for the Lake Tashmoo system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Tashmoo - main basin	MV21	0.300	0.288	-38.6%
Tashmoo - main basin	MV1	0.311	0.297	-35.5%
Tashmoo - main basin	MV2	0.329	0.306	-39.8%
Tashmoo - main basin	MV3	0.369	0.330	-39.3%
Drew Cove	MV4	0.385	0.343	-37.1%
Upper Lake Tashmoo	MV5	0.423	0.375	-31.5%

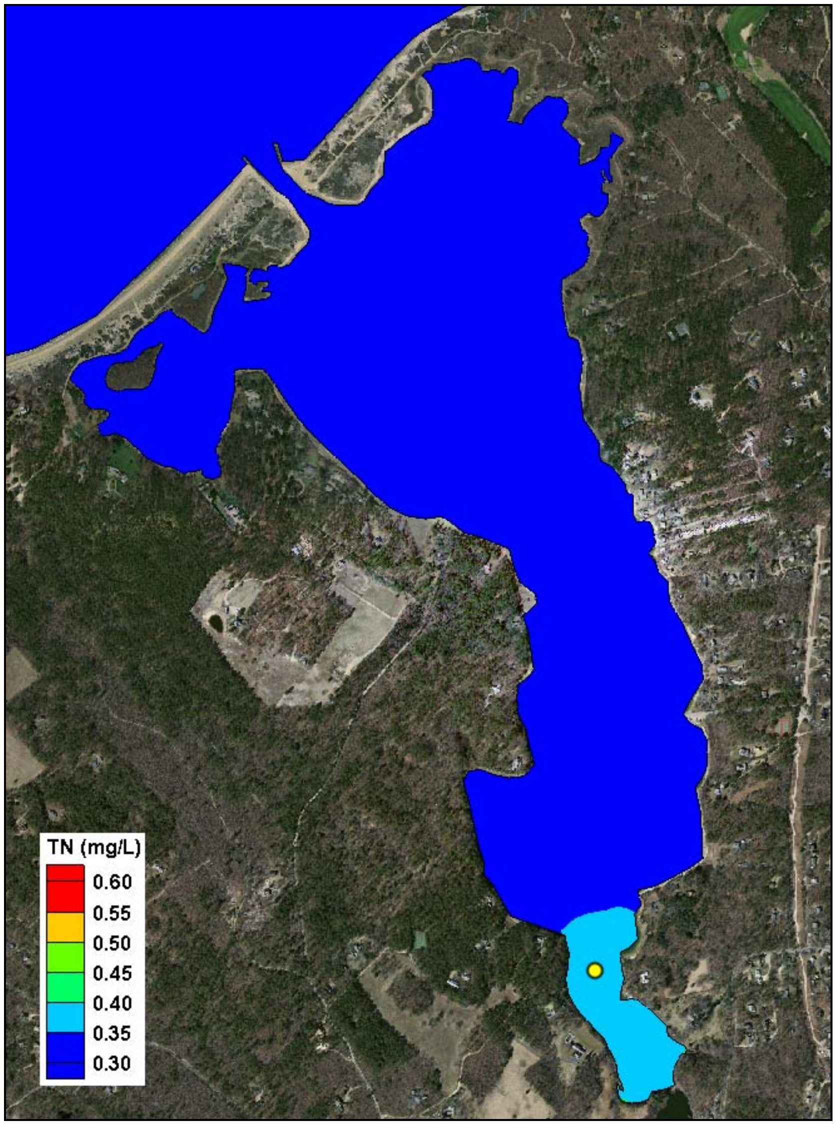

Figure VIII-1. Contour plot of tidally averaged modeled total nitrogen concentrations (mg/L) in the Lake Tashmoo system, for threshold. The yellow marker indicates the site of the sentinel station, which represents the inner edge of historical eelgrass coverage.

IX. MANAGEMENT SCENARIO: ALTERNATIVE WATERSHED DELINEATIONS

IX.1 BACKGROUND

The Town of Tisbury is currently conducting an Effluent Disposal Project. This project is reviewing the current discharge sites utilized for the Town's wastewater treatment facility (WWTF) and evaluating potential options to develop one additional site. As mentioned in Section IV, one of the existing sites is located outside of the Lake Tashmoo watershed and the other straddles its eastern boundary. The town's wastewater consultants, Wright-Pierce (WP), recently prepared a groundwater modeling report with the modeling firm of Watershed Hydrogeologic Inc. (WH), which updated a portion of the Tisbury groundwater model in order to review the potential impacts of discharging various volumes of treated effluent at three sites: the two existing locations and an third near the town elementary school (WP/WH, 2013).

The groundwater modeling was completed to: 1) review potential water level mounding under the sites during wastewater discharge, 2) the direction of groundwater flow from each site at various discharge rates and 3) review the watershed boundaries for the portions of Lake Tashmoo and Lagoon Pond within the model domain (Figure IX-1). The review of watershed boundaries is important for the purposes of evaluating how much of the effluent discharge from the Town WWTF is impacting the surrounding estuaries. The groundwater modeling for the Tisbury Effluent Disposal Project shows that two of the wastewater discharge sites being reviewed (Elementary School and Public Works sites) are outside of the Tashmoo watershed. This finding is consistent with the MEP/MVC watershed delineations. The third site, Town Hall Annex, is located on the Lake Tashmoo watershed boundary in the MEP/MVC delineation and remains on the boundary in the revised modeling. However, other portions of this boundary show some differences between the two delineations.

MEP staff have a number of concerns about the groundwater modeling and have submitted a series of clarifying questions to the town's consultants, but agreed to evaluate the nitrogen loading difference between the boundaries for the portion of the Lake Tashmoo watershed that is in the model domain. Unlike the MVC/MEP watershed delineation, the Effluent Disposal Project watershed only addresses approximately 20% of the outer watershed boundary to Lake Tashmoo. As would be expected for the relatively limited model domain, the watershed boundaries are not associated with a comprehensive watershed delineation including the other estuaries on Martha's Vineyard or even adjacent watersheds, such as that for Lagoon Pond. For the purposes of the present management scenario, MEP staff worked with the town's consultants to determine parcels located in the "sliver" of land between the MEP/MVC watershed and the WP/WH watershed (Figure IX-2). The nitrogen loads for these parcels were determined from the MEP watershed nitrogen loading model (see Section IV.1) and MEP staff determined the difference in load.

IX.2 SCENARIO RESULTS

Generally the WP/WH watershed line is on the western side of the MVC/MEP watershed line (*i.e.*, closer to Lake Tashmoo). However, in the area of the existing Town Hall Annex wastewater disposal beds, the WP/WH watershed line crosses over the MVC/MEP watershed line thereby including more of the effluent disposal beds within the Lake Tashmoo watershed. But the areal difference is small, approximately 27 acres or 1% of the overall MEP/MVC watershed. This difference is negligible relative to the freshwater input to Lake Tashmoo from its watershed (i.e. flow is virtually the same from both delineated watersheds).

In order to estimate the potential nitrogen loading difference associated with the region between the two watershed boundaries, MEP staff selected parcels within the “slivers” and reviewed the placement of buildings and likely septic system leachfields based on best professional judgment. This review identified 48 parcels within the slivers, 41 of which were developed and currently have a wastewater nitrogen load. Among these 41 parcels, 23 were single family residences. For the purposes of estimating wastewater nitrogen loadings, 35 of the 41 developed properties have measured water use and 6 are estimated to have private wells. Using all the standard and Lake Tashmoo specific nitrogen loading factors used for calculating the watershed loads (see Section IV.1), MEP staff determined that the total nitrogen load within the “slivers” was 328 kg/yr. This load is 4.5% of the watershed load determined in Section IV.1 for the Lake Tashmoo Main sub-watershed and it is 3.1% of the overall total Lake Tashmoo annual nitrogen load. These changes in loads were not run through the water quality model because this was beyond the scope of this scenario (as agreed to by all parties), but this small difference approaches the margin of the predictive ability of the water quality model, especially given the differences in delineation approaches. Further, the small load difference is unlikely to change the water quality concentrations within the estuary in any meaningful way given where the load enters estuarine waters. The MEP team is available to discuss other options to manage water quality in the Lake Tashmoo Estuary using the linked MEP models with any of the towns within the watershed.

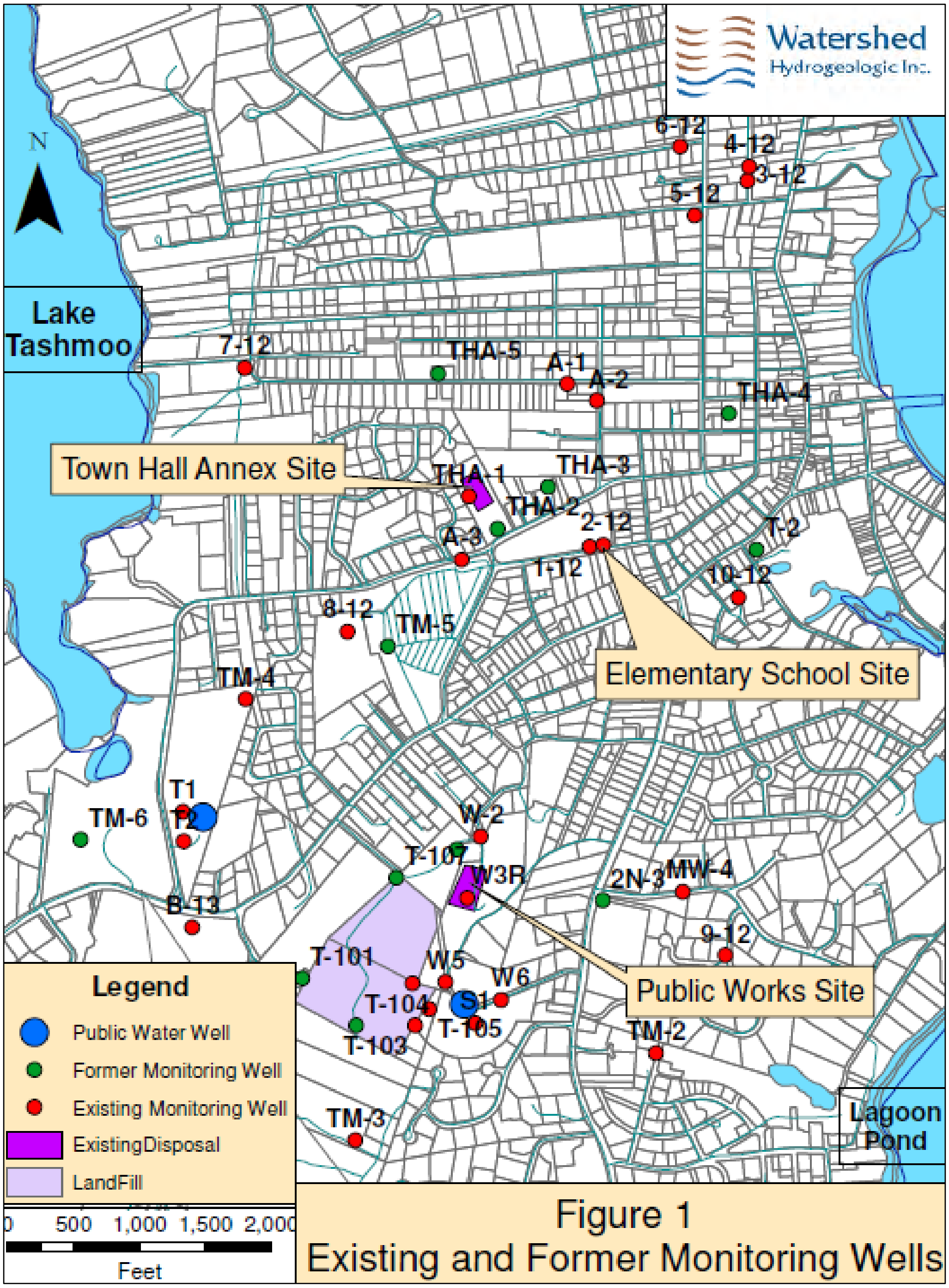

Figure IX-1. Approximate Town of Tisbury Effluent Disposal Project groundwater model domain. This figure shows the three effluent disposal sites that the Town is assessing: the Town Hall Annex and Public Works sites are already used for effluent disposal from the Town wastewater treatment facility and the Elementary School site is being assessed for future use. It should be noted that the area evaluated by the groundwater model only includes a small portion of the whole watershed area to Lake Tashmoo, mainly a portion of its eastern boundary. This figure is modified from Figure 1 in WP/WH (2013).

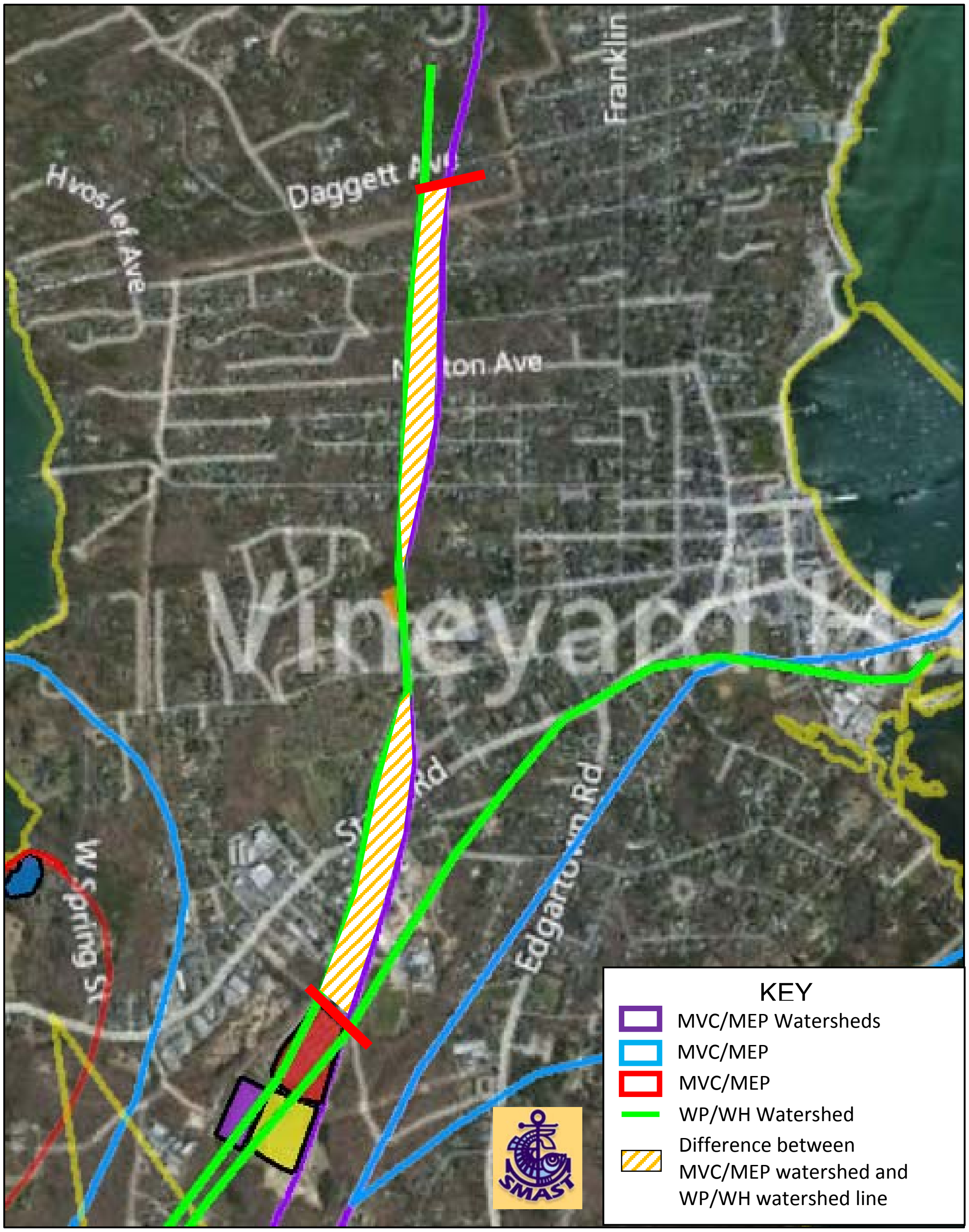

Figure IX-2. Lake Tashmoo watershed delineation differences between MVC/MEP and modeled WP/WH watershed lines. Areas indicated with the orange/white striping indicate the areas of difference between the two watershed delineations. The total area of difference is approximately 27 acres. WP/WH watershed lines are generally closer to Lake Tashmoo except in the area of Town Hall Annex effluent discharge site, where the MVC/MEP line is closer. MVC/MEP lines include the whole Lake Tashmoo watershed, comprehensive island-wide watersheds, and subwatersheds to various estuary sub-basins. WP/WH watershed lines do not share these important characteristics and are based on the model domain in Figure IX-1.

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