Massachusetts Department of Environmental Protection

The School for Marine Science and Technology
University of Massachusetts Dartmouth

Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Lagoon Pond Embayment System, Oak Bluffs and Tisbury, Massachusetts

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

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

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

In particular, the Lagoon Pond embayment system within the Towns of Oak Bluffs and 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 Oak Bluffs and Tisbury have recognized the severity of the problem of eutrophication and the need for watershed nutrient management and are currently engaged in wastewater management at a variety of levels. Moreover, the Towns of Oak Bluffs and Tisbury are working collaboratively regarding the future implementation of the MEP nutrient threshold analysis of the Lagoon Pond system. For the Town of Oak Bluffs, this analysis of the Lagoon Pond system will be considered relative to the recently completed nutrient threshold analysis of Farm Pond and Sengekontacket Pond to plan out and implement a unified town-wide approach to nutrient management for Oak Bluffs. The Towns of Oak Bluffs and Tisbury 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 Lagoon Pond embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Martha's Vineyard Commission and the Town of Oak Bluffs and Tisbury. The water quality monitoring program was conducted with technical guidance from the Coastal Systems Program at SMAST (see Section II). Evaluation of upland nitrogen loading was conducted by the MEP and data was provided by the Planning Departments in the Towns of Oak Bluffs and Tisbury 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 Lagoon Pond 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 Lagoon Pond embayment system and each of the systems sub-embayments as appropriate (current and build-out loads are summarized in Section IV). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

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

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

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

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Lagoon Pond embayment system in the Towns of Oak Bluffs and Tisbury. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment, however, within this report an additional hydrodynamic analysis was completed on a culvert modification scenario. Hydrodynamic and water quality model runs were performed to investigate quantitatively how flushing and TN concentrations would change in the Lagoon Pond system if culverts were placed under Beach Road, between the South End Basin and Vineyard Haven Harbor. For the analysis, a total of six eight-foot-wide culverts were placed in the model at specific locations described in Section IX.

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 76% of the controllable watershed load to the Lagoon Pond embayment system and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through this source is a good gauge of the feasibility for restoration of these systems.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Lagoon Pond embayment system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure. At present, the Lagoon Pond Estuary is showing nitrogen enrichment and impairment of both eelgrass and infaunal habitats (Section VII), indicating that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system. The system is showing some nitrogen related habitat impairment throughout its tidal reaches. The East Arm historically has supported fringing eelgrass beds, presumably due to the limitation of the depth of eelgrass growth by light limitation in the deep basins. While fringing eelgrass beds are still found in each of the basins of the East Arm, their coverage is being reduced to shallower areas and also being disproportionately lost in the upper and mid basins. The pattern of loss is consistent with nitrogen enrichment. 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 by the MEP for these areas. The West Arm has not historically supported stable eelgrass beds and at present the infaunal communities in this portion of the system are moderately impaired. However, given the level of impairment and the location of the West Arm within the Lagoon Pond System, it is certain that restoring eelgrass habitat within the upper basin of the East Arm will result in restoration of the infaunal habitat in the West Arm, as nitrogen enrichment will be significantly reduced to the overall estuary (Section VIII.3).

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 (>4 meters) of Lagoon Pond under moderately nutrient enriched conditions. The chlorophyll-a levels also indicate only moderate nitrogen enrichment, while the bottom water oxygen levels show prolonged hypoxia and periodic anoxia in deep waters. It appears that the basins which comprise much of the bottom habitat of Lagoon Pond are periodically not vertically well mixed during the summer, which allows the moderate level of nutrient enrichment to produce very low oxygen conditions on a frequent basis. 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 follow the spatial pattern of total nitrogen levels in this system. It is clear that the nutrient enrichment response in Lagoon Pond is magnified by its basin structure combined with the depositional nature of the deep basins. The result is poor quality benthic animal habitat within the deeper waters of the basins of the Eastern Branch. The lack of eelgrass in these areas is almost certainly a result of their depth (4-10 meters). The observed gradient in nitrogen enrichment and chlorophyll-a levels is consistent with the pattern of eelgrass habitat decline throughout the estuary and indicate only a moderate level of nitrogen enrichment. However, given the structure of the estuary, eelgrass is becoming restricted to shallower depths, resulting in loss of habitat primarily within the upper and mid basins of the Eastern Arm of Lagoon Pond.

Eelgrass bed coverage within Lagoon Pond has been declining since 1995 (possibly even back to 1987). The pattern of bed loss showing "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 Lagoon Pond, as well. However, the persistence of fringing beds in the upper basin suggests that nitrogen enrichment is moderate, which is also consistent with the observed chlorophyll-a levels. The continuous losses of bed area from 1995-2006 indicate that habitat decline and nitrogen enrichment is continuing.

As eelgrass within Lagoon Pond 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 the Lagoon Pond Embayment System. It should be noted that since there is little evidence of the deep basins of the East Arm and virtually all of the West Arm ever having had eelgrass habitat, establishment of eelgrass in these basins cannot be supported as a specific restoration goal. Management of nitrogen levels through reductions in watershed nitrogen inputs and increased tidal flushing, as appropriate, are required for restoration of eelgrass and infaunal habitats within the Lagoon Pond Embayment System.

The survey of infauna communities throughout Lagoon Pond indicated a system presently supporting impaired benthic infaunal habitat in the shallow basin and degraded habitat within the deep basins as a result of periodic hypoxia/anoxia in summer. The loss of the deep basin infauna habitat results form the observed periodic reduction in vertical mixing by the weak salinity stratification of waters in these deep basins. The effect of the geomorphology of the basins in Lagoon Pond is to increase deposition of organic matter (increasing oxygen uptake from bottom waters) and the "isolation" of 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 ($\geq$4 meters) are not supportive of infaunal communities. The large areas of bottom at these depths have significantly degraded (extremely poor) habitat for infaunal animals. The infaunal habitat quality in the East and West Arms of Lagoon Pond was consistent with the observed levels of dissolved oxygen, chlorophyll, nutrients and organic matter enrichment as well as basin structure within each component of the system. The tributary sub-embayment basin of the West Arm of Lagoon Pond is presently supporting moderately impaired benthic habitat, while the main East Arm of the Lagoon Pond system is generally showing signs of significant degradation of infaunal habitat (very poor quality), partially due to depth and basin geomorphology. It should be noted that habitat quality of the East Arm of Lagoon Pond is best indicated by eelgrass habitat and the West Arm by benthic community characteristics, and that restoring these habitats should be the focus of the nitrogen management threshold analysis (Section VIII.2).

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 Lagoon Pond system in the Towns of Oak Bluffs and Tisbury were comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 76% of the controllable watershed nitrogen load to the embayment was from wastewater.

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

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

Lagoon Pond Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Lagoon Pond system should reflect both recent pre-degradation habitat quality and be reasonably achievable. Based upon the assessment data (Section VII), the Lagoon Pond 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 East Arm compared to shallower areas in the lower portion of the East Arm as well as the West Arm).

- The primary habitat issue within the Lagoon Pond Embayment System relates to the general loss of eelgrass beds and impaired infaunal habitat. Fringing eelgrass beds within the upper reach of the Eastern Arm of the estuary have declined significantly from 1995-2006. Since there is little evidence that the deep basins of the East Arm and the West Arm ever supported stable eelgrass habitat, establishment of eelgrass in these basins is not included as a specific restoration goal. Within the shallow Western Arm, infaunal habitat is presently moderately impaired by nitrogen and organic matter enrichment, while infaunal habitat within the deep basins of the Eastern Arm is virtually absent due to periodic hypoxia/anoxia. It should be noted that habitat quality of the East Arm of Lagoon Pond is best indicated by eelgrass habitat and the West Arm by benthic community characteristics. Restoring these habitats is the focus of the nitrogen management threshold analysis (Section VIII.3).

- The absence of eelgrass within the West Arm 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. In contrast, some stable eelgrass beds were observed within the lower basin at tidally averaged nitrogen levels of 0.328 mg N L^{-1}, while fringing eelgrass beds presently exist in the shallow margins of the upper and mid basin at nitrogen levels between 0.371 mg N L^{-1} and 0.338 mg N L^{-1}. These TN levels and habitat stability/decline are consistent with persistence and loss of eelgrass at similar depths in other estuaries on Vineyard/Nantucket Sound.

- The threshold for stable eelgrass habitat in Lagoon Pond must be less than 0.385 mg N L-1, as this is the present level and loss is continuing. Similarly, it appears that eelgrass beds presently exist in Lagoon Pond at nitrogen levels between 0.371 mg N L^{-1} and 0.338 mg N L^{-1}. However, at the higher end of this range some loss is continuing. Based upon these observations and those from other similar systems in the MEP study region, a tidally averaged nitrogen threshold for Lagoon Pond of 0.35 mg N L-1 will allow restoration of the impaired eelgrass habitat. This threshold is for the sentinel station LGP-2, located at the upper extent of the major fringing beds observed in 1995. The historically noted small narrow beds between the sentinel station and the headwaters should also be restored as these were mainly restricted to areas of shallow water. 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 in the Western Basin.

For restoration of the Lagoon Pond Embayment System, the primary nitrogen threshold at the sentinel station will need to be achieved. At the point that the threshold level is attained at the sentinel station, water column nutrient concentrations will also be at a level that will be supportive of healthy infaunal communities. The results of the Linked Watershed-Embayment modeling are used to ascertain that when the nitrogen threshold is attained, TN levels in the regions associated with the secondary criteria of healthy infauna are also within an acceptable range. The goal is to achieve the nitrogen target at the sentinel location and restore healthy eelgrass habitat throughout the lower and upper region of the Lagoon Pond 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 Lagoon Pond estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that significant increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. Therefore, watershed-estuarine nitrogen management must include management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Lagoon Pond estuarine system is that restoration will necessitate a reduction in the present (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 Lagoon Pond system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Lagoon Pond system include both upper watershed regions contributing to the major surface water inputs.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
LAGOON POND SYSTEM										
Lagoon Pond	1.827	36.208	27.580	-	36.208	7.156	36.756	80.121	0.36-0.42	0.35
South End Basin	0.164	5.762	4.770	-	5.762	0.921	10.105	16.788	-	-
Upper Lagoon Pond	0.529	4.827	2.060	-	4.827	-	-	4.827	0.33-0.39	-
Lagoon Pond System Total	**2.520**	**46.797**	**34.410**	**-**	**46.797**	**8.077**	**46.862**	**101.736**	**0.33-0.42**	**0.35**

1 assumes entire watershed is forested (i.e., no anthropogenic sources)
2 composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
3 existing attenuated wastewater treatment facility discharges to estuary
4 composed of combined present land use, septic system, and WWTF 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 data collected between 2002 and 2007, ranges show the upper to lower regions (highest-lowest) of the indicated sub-embayment.
8 eelgrass threshold for sentinel station in Lagoon Pond at water quality monitoring station LSP-2.

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

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
LAGOON POND SYSTEM						
Lagoon Pond	36.208	22.418	7.156	26.650	56.224	-38.1%
South End Basin	5.762	3.377	0.921	8.717	13.014	-41.4%
Upper Lagoon Pond	4.827	4.827	-	-	4.827	+0.0%
Lagoon Pond System Total	**46.797**	**30.622**	**8.077**	**35.368**	**74.066**	**-34.6%**

(1) Composed of combined natural background, fertilizer, runoff, WWTF, 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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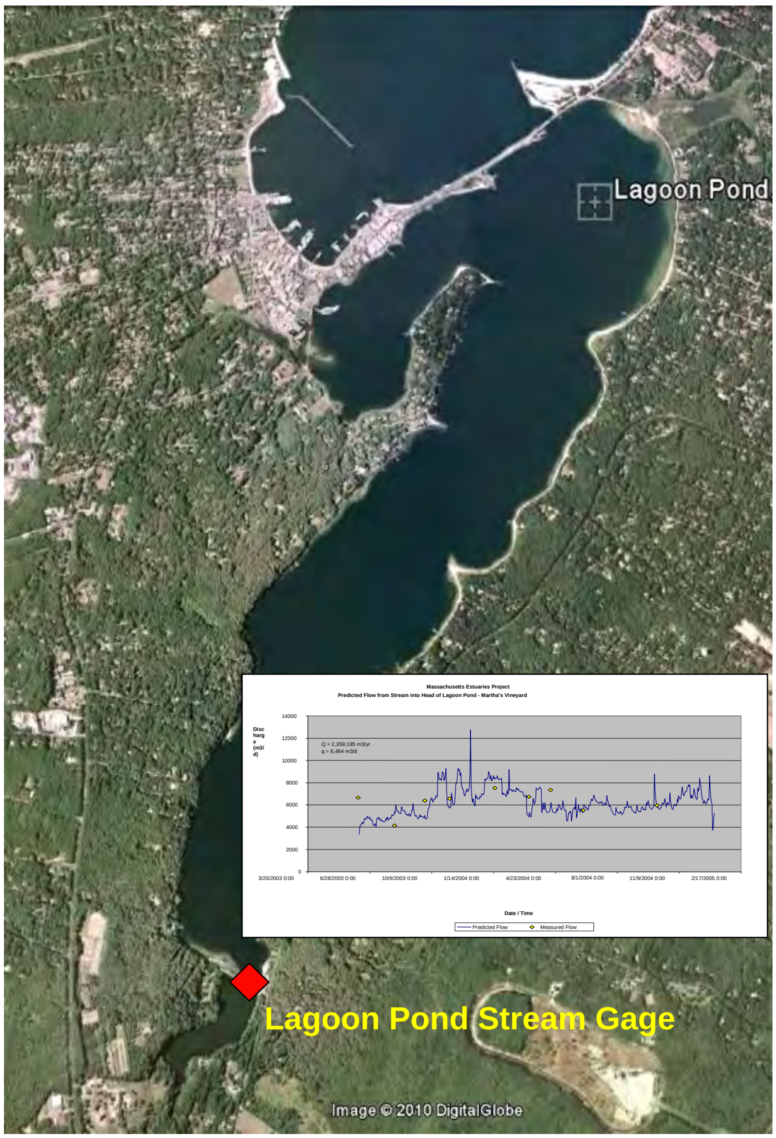

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First and foremost we would like to recognize and applaud the significant time and effort in data collection and discussion spent by members of the Martha's Vineyard Commission and the Towns of Oak Bluffs and Tisbury Shellfish Department's Water Quality Monitoring Program. These groups worked with SMAST-Coastal Systems Program scientists to develop a consistent and sound nutrient related water quality monitoring program for this system, and all four parties spent time in conducting the requisite field sampling. Without this high quality data the present analysis of Lagoon Pond would not have been possible. In addition, we are grateful to the foresight of Tisbury Waterways in jump starting the MEP analysis of this system through its partial funding of the hydrodynamic analysis.

In addition, staff from the Martha's Vineyard Commission and the Towns of Oak Bluffs and Tisbury have provided essential insights toward this effort. Of particular note has been the effort of the late Derek Cimeno (Town of Tisbury Shellfish Constable) who was an enthusiastic champion for restoration of the health of Lagoon Pond and the shellfish resources it supports. His commitment and energy are missed. We would also like to extend a special thanks to Dave Grunden (Oak Bluffs Shellfish Constable) and Bill Wilcox (MVC Water Resource Planner) for providing historical information and reports on Lagoon Pond and Chris Seidel, GIS Specialist from the MVC for providing land-use information and GIS support. We are equally grateful for the help we received from the staff at the Massachusetts State Lobster Hatchery who supported the MEP Technical Team during a critical data collection phase of the project.

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I. INTRODUCTION

The Lagoon Pond Embayment System is a simple estuary located within the Towns of Oak Bluffs and 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 Lagoon Pond watershed is distributed amongst the Towns of Oak Bluffs and Tisbury, with a large region of the upper watershed comprised primarily of "protected" forest land (Martha's Vineyard State Forest). Although 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 Lagoon Pond System will require consideration of all sources of nitrogen load. That the entire watershed to the Lagoon Pond system lies primarily within the "Towns of Oak Bluffs and Tisbury with small portions within the Towns of Edgartown and West Tisbury makes development and implementation of a comprehensive nutrient management and restoration plan for this system more challenging as watershed-wide planning can sometimes be complicated by the need for consensus among multiple municipal jurisdictions.

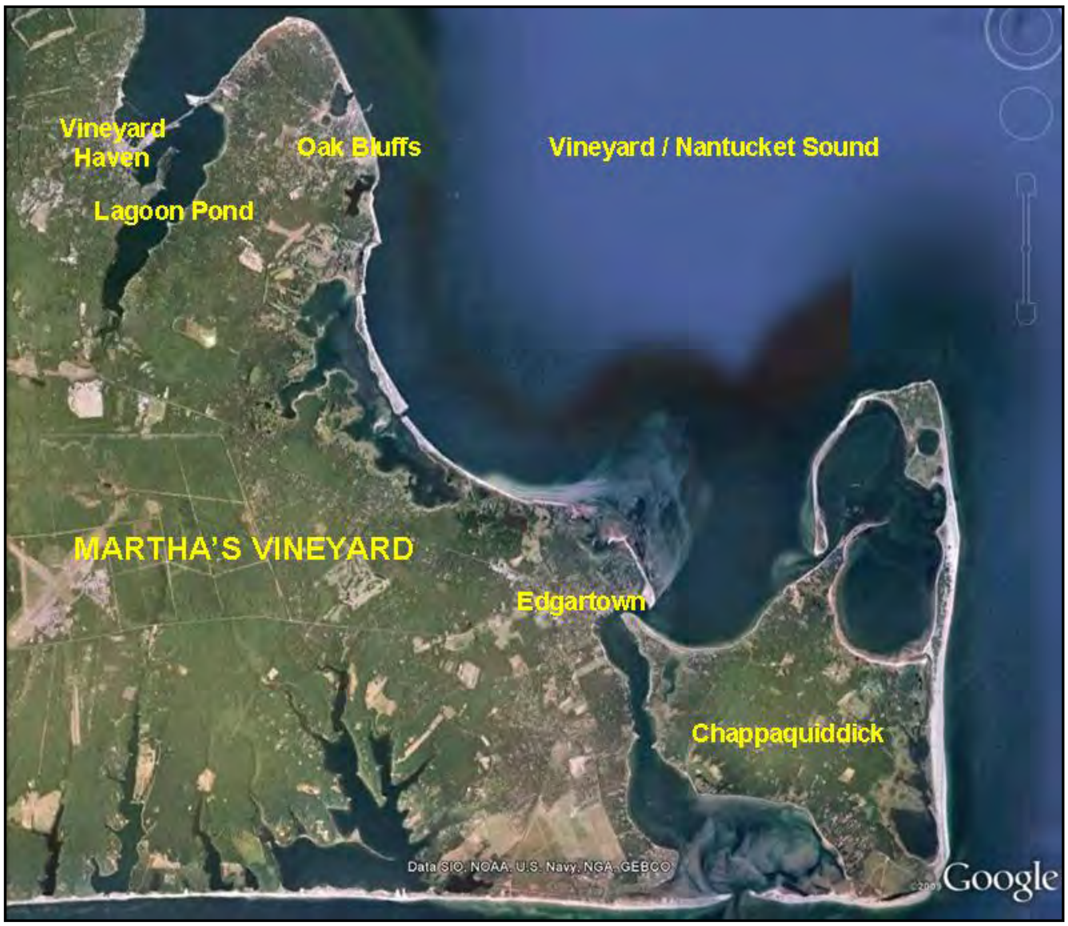


Figure I-1. Location of the Lagoon Pond system on the north shore of the Island of Martha's Vineyard within the Towns of Oak Bluffs and Tisbury, MA. Lagoon Pond is a drowned valley enclosed by a barrier beach, with a single tidal inlet through which tidal waters are exchanged with Vineyard Sound.

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 that they receive due to the proximity and density of development near and along their shores. The presence of tributary coves (e.g. West Arm (South End Basin) to Lagoon Pond) to the Lagoon Pond System greatly increases the shoreline and with the head water stream, decreases the travel time of groundwater (and its pollutants) from the watershed recharge areas to bay regions of discharge. In particular, the Lagoon Pond system and its tributary cove, along with many of the other salt pond systems on Martha's Vineyard such as Sengekontacket Pond, Lake Tashmoo, Farm Pond and James Pond, are at risk of eutrophication (over enrichment) from high nitrogen loads in the groundwater and runoff from the watershed and numerous sub-watersheds.

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

The Towns of Martha's Vineyard have been among the fastest growing towns in the Commonwealth over the past two decades and the Town of Oak Bluffs and Tisbury do have centralized wastewater treatment systems, however, these facilities are limited in size and reach and therefore do not receive wastewater from areas within the watershed to Lagoon Pond. Rather, 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 Oak Bluffs and Tisbury, water quality degradation will accelerate, with further harm to invaluable environmental resources of the Towns and the Island on the whole.

As the primary stakeholders to the Lagoon Pond system, the Towns of Oak Bluffs and Tisbury, in collaboration with the Martha's Vineyard Commission (MVC), have been among the first communities to become concerned over perceived degradation of their coastal embayments. Over the years, this local concern has led to the conduct of numerous studies (see Chapter II) of both barrier beach stability and nitrogen loading to the system such as: 1) the Lagoon Pond Study: Assessment of Environmental Issues and Observations on the Estuarine System, WHOI 1986, 2) Nutrient Loading to Lagoon Pond, Martha's Vineyard Commission 2000, 3) Diagnostic/Feasibility Study for Lagoon Pond, Oak Bluffs/Tisbury, SP Engineering, 1986, 4) Lagoon Pond Drawbridge studies completed by Parson's Transportation Group and 5) Lagoon Pond Hydrographic Survey, Martha's Vineyard Commission, 1977. While critical historical studies have been considered in the MEP analysis of Lagoon Pond, key in the MEP effort has been the Lagoon Pond Water Quality Monitoring Program, spearheaded by the MVC and supported by private, municipal, county and state funds (most recently Massachusetts 604(b) grant program) with technical assistance by the Coastal Systems Program at SMAST-UMD. This effort provides the quantitative water column nitrogen data (2002-2007) required for the implementation of the MEP Linked Watershed-Embayment Approach used in the present study.

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

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

While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff, 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 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 Lagoon Pond System and its associated watershed has been significantly altered by human activities over the past ~100 years. As a result, the present nitrogen "overloading" appears to result partly from alterations to its ecological systems. These alterations subsequently affect nitrogen loading within the watershed and influence the degree to which nitrogen loads impact the estuary. Therefore, restoration of this system should focus on managing nitrogen through both management of nitrogen loading within the watershed and restoration/management of processes which serve to lessen the amount or impact of nitrogen entering the estuary.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

The primary nutrient causing the increasing impairment of the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within Southeastern Massachusetts alone, almost all of the municipalities (as is the case with the 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 a coastal TMDL working group 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 TMDL analysis, outreach, and planning,
- keep each embayment's model "alive" to address future municipal needs.

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

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

The Linked Model has been applied for watershed nitrogen management in approximately 40 embayments throughout Southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach's greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options.

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

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

The Lagoon Pond Embayment System is a simple estuary, with a single armored inlet through the barrier beach across which spans the Beach Road drawbridge. Lagoon Pond is a long narrow north/south oriented system that has one small tributary cove referred to as the West Arm (South End Basin), with the main tidal reach consisting of a lower (North basin), middle (Central basin) and upper basin (South basin). Tidal water from Vineyard Sound enters the basin at the lower end of the eastern arm or branch and circulates through channels and across flats moving up the East Arm or into the much smaller shallow West Arm (Figure I-3). Lagoon Pond 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 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 Wisconsinan Laurentide ice sheet reached its maximum extent and southernmost position about 20,000 years before present (BP), as indicated by the presence of terminal moraines on Martha's Vineyard and Nantucket and the southern limit of abundant gravel on the sea floor of Nantucket Sound and Vineyard Sound (Schlee and Pratt, 1970; Oldale, 1992; Uchupi et al., 1996). The lobate ice front was comprised of the Buzzards Bay lobe that deposited the moraine along the western part of Martha's Vineyard, the Cape Cod Bay lobe that deposited the moraines across eastern Martha's Vineyard and Nantucket, and the South Channel lobe that extended east toward Georges Bank (Oldale and Barlow, 1986; Oldale, 1992). During the retreat of the ice sheet, approximately 18,000 years BP, the Nantucket Moraine was deposited 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 Lagoon Pond is a much more recent formation, likely 2,000 - 4,000 years ago as sea level flooded the present basin.

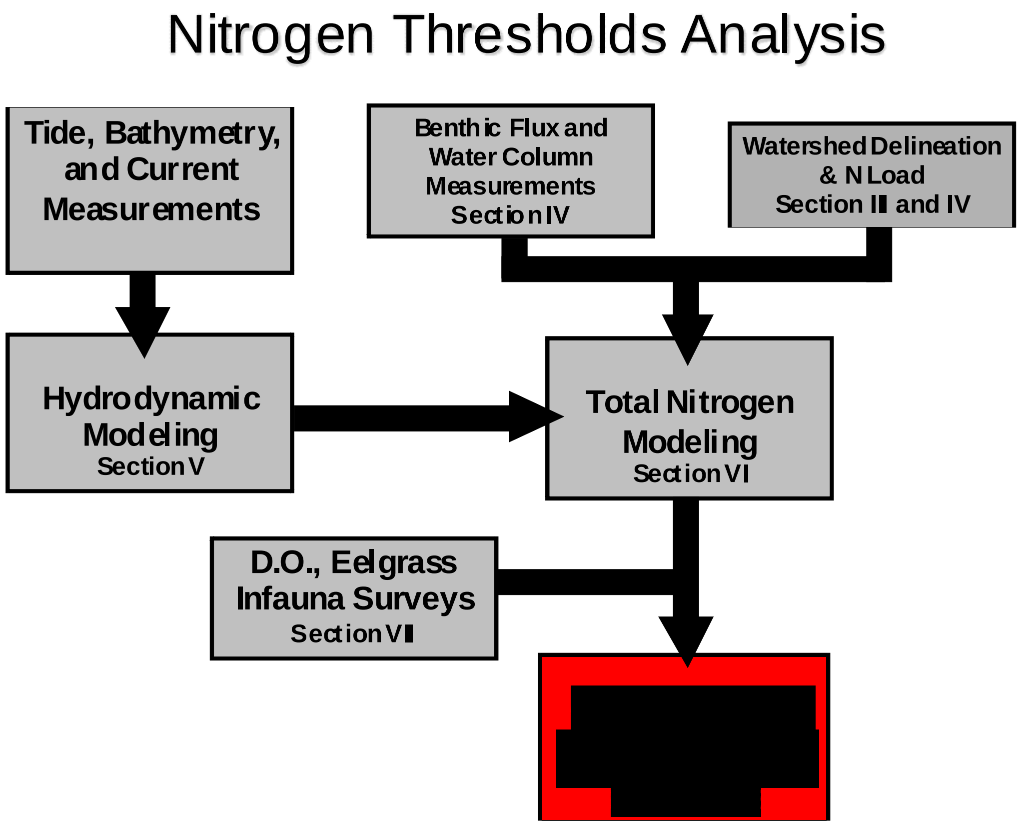


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

The enclosed Lagoon Pond 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 Lagoon Pond favors its formation as a "lagoon". What is clear is that it is presently functioning as an estuarine system and is showing signs of nitrogen enrichment. For the MEP analysis, the Lagoon Pond estuarine system was considered as 2 tributary sub-embayments, with the eastern branch being divided into upper (North), mid (Central) and lower (South) sub-basins based upon geomorphologic features (see Figure I-3).

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

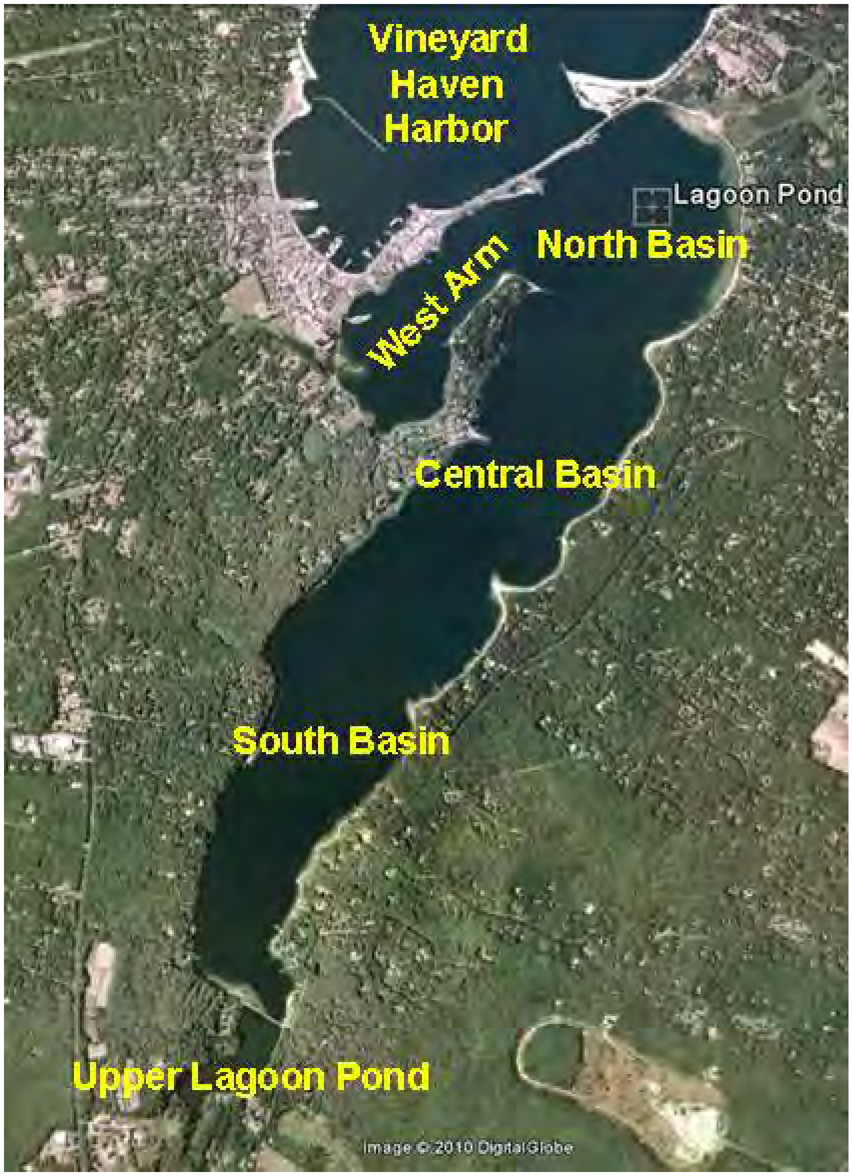


Figure I-3. Estuarine basins for the Massachusetts Estuaries Project analysis of the Lagoon Pond Embayment System. Tidal exchange with Vineyard Sound waters is through the single inlet through the barrier beach. Sound waters enter after first passing through Vineyard Haven Harbor. Freshwaters enter from the watershed primarily through direct groundwater discharge with a small outflow from Upper Lagoon Pond which is freshwater and artificially created when dirt road was built.

I.3 NUTRIENT LOADING

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

Nutrient related water quality decline represents one of the most serious threats to the ecological health of the nearshore coastal waters of Massachusetts 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 Lagoon Pond System monitored by the Martha's Vineyard Commission and the Towns of Oak Bluffs and Tisbury. The Water Quality Monitoring Program with 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 the Lagoon Pond System 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 this salt pond 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 with continuing losses moving from the headwater beds to the inlet). In addition, infaunal animal habitat has been lost in some basins due to organic matter enrichment and oxygen depletion resulting from nitrogen enrichment. Nitrogen related habitat impairment within the Lagoon Pond Estuary shows a gradient moving from the inland reaches toward the inlet. The result is that nitrogen management of the primary basin (East Arm) and tributary cove (West Arm) of the Lagoon Pond system is aimed at restoration, not protection or maintenance of existing conditions. Fortunately for the citizens of Oak Bluffs and Tisbury, Lagoon Pond 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 systems and contributed to the degradation in ecological health, the Lagoon Pond system generally receives high quality (low nitrogen) tidal waters from Vineyard Sound that are apparently little amended by passage through Vineyard Haven Harbor. The quantitative role of the tidal inlet and the associated bridge opening 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 Lagoon Pond System; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within each system. Therefore, water quality modeling of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. The spread of pollutants may be analyzed from tidal current information developed by the numerical models.

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

Using standard dispersion relationships for 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 Lagoon Pond System is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Vineyard Sound source waters and throughout the Lagoon Pond system were taken from the Town of Oak Bluffs-Tisbury/MVC Water Quality Monitoring Program (a coordinated effort between the Towns of Oak Bluffs, 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 (2002-2007) were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Lagoon Pond System for the Towns of Oak Bluffs and 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 Pond in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration of the Pond. This latter assessment represents only one of many solutions and is produced to assist the Towns in developing a variety of alternative nitrogen management options for this system. Finally, analyses of the Lagoon Pond System were undertaken relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and examine inlet widening to improve nitrogen related water quality. The results of the nitrogen modeling for each scenario have been presented in Section VIII.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

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

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

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

Lagoon Pond Study: An Assessment of Environmental Issues and Observations on the Estuarine System. - Prior to the Massachusetts Estuaries Project, a preliminary analysis of the problems and issues affecting environmental quality of Lagoon Pond as well as basic nutrient characteristics and tidal exchange in the System was prepared (Gaines, 1986) for the Boards of Selectmen of both the Town of Oak Bluffs and the Town of Tisbury, Martha's Vineyard, Massachusetts. The study included an initial assessment of public health concerns, conflicting uses of the system, shellfishing considerations, navigation and the effect of moorings. The report also endeavored to characterize watershed nitrogen loading to the Lagoon Pond estuary based on land use and make a link to the observed decreases in environmental quality in the pond. Much of the nitrogen loading analysis was based on estimates of land use acreages and the watershed delineation at the time. While the results gave a general view as to the approximate nitrogen loading, the watershed delineation was significantly different than the watershed delineations used by the MEP, which have the benefit of the USGS advanced numerical models that did not exist 30 years ago. In addition, the MEP analysis is able to use a parcel-by-parcel approach to land-use analysis for nitrogen loading rates, rather than the total acreage approach, which is still used for very large watersheds (e.g. Taunton River) but generally not for smaller systems like Lagoon Pond. For these reasons and many others, the land use analysis conducted previously as compared to that undertaken by the MEP is significantly different. The present MEP approach builds on the earlier effort with improved techniques not available 25 years ago and as a result is a more accurate watershed nitrogen analysis suitable for site-specific planning purposes.

The important message to capture from the earlier analysis is that by 1986 it was already becoming apparent that there was a connection between decreased environmental quality in Lagoon Pond and increased nitrogen loading from human activities in the watershed. The report further noted that while the link between environmental quality and nutrients entering from the watershed was not completely understood, watershed land use management would clearly be key to managing increases of nutrients that would likely result in further degradation of the estuary. Twenty-five years later the MEP analysis supports this latter conclusion and fortunately science now provides the necessary analytical tools for use by the MEP to link watershed nitrogen loading to tidal hydrodynamics and internal cycling. This more powerful tool, not previously available, is what is now being used to provide a site-specific assessment and threshold as well as the guidance for restoration of this estuarine system.

Diagnostic/Feasibility Studies related to the Lagoon Pond System – Complementing the initial environmental assessment work on Lagoon Pond as undertaken by Gaines (Gaines 1986), in 1986 SP Engineering was retained by the Towns of Oak Bluffs and Tisbury to conduct a diagnostic/feasibility study of the Lagoon Pond system. As part of the overall study, a survey of macroalgae presence in Lagoon Pond was of specific relevance to the current MEP analysis of the Lagoon Pond system.

In addition, Upper Lagoon Pond was also examined in 1986 (Poole, 1986). This study included collection of eleven (11) water quality samples between March 1986 and September 1987, limited measurement of stream outflow, and one rainfall impact assessment. At the time of this study, the outlet configuration allowed the highest of tides to have a direct connection between Upper Lagoon Pond and the Lagoon Pond estuary. This yielded an important comparison to present Upper Lagoon Pond, which is presently fresh water.

Martha's Vineyard Commission: Nutrient Loading to Lagoon Pond 2000 – Increasing concern over the decrease of habitat quality in the Lagoon Pond Estuary led the Martha's Vineyard Commission to seek a 604B grant from the Massachusetts Department of Environmental Protection to conduct a watershed nutrient loading analysis of the Lagoon Pond system. The main objective was the establishment of a justifiable nitrogen loading limit that would slow down the pace of degradation in the Lagoon Pond system. Fundamental to the analysis completed by the MVC in 2000 was a more comprehensive land use analysis than was undertaken by Gaines in 1986. Additionally, building on previous watershed delineations completed by Clifford Kaye in 1977 and David Delaney of the USGS in 1980, the MVC utilized new information on water table elevations to refine the watershed delineation for use in its nutrient loading assessment. In the MVC analysis, water quality data and information on the presence and distribution of eelgrass and macroalgae was combined with the watershed nitrogen loading estimates and basic calculations of water residence times from tidal stage measurements to determine a nitrogen loading limit for the pond. Since the major focus was quantifying watershed nitrogen loading, linkage of nitrogen inputs to tidal hydrodynamics was beyond the scope of this effort. However, the MVC 2000 analysis determined that a 17,000 kg/yr limit on Total Nitrogen entering Lagoon Pond would maintain habitat quality at its existing level. The pertinent aspects of the overall analysis and results were taken into consideration by the MEP as a historical back drop for the current analysis.

MVC/Town of Oak Bluffs and Tisbury 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 Lagoon Pond in the Town of Oak Bluffs and Tisbury. The Martha's Vineyard Commission working with the Town of Oak Bluffs and Tisbury Shellfish Departments coordinated and executed the water quality surveys of the Lagoon Pond System. For Lagoon Pond 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. This baseline water quality data are a prerequisite to entry into the MEP and the conduct of its Linked Watershed-Embayment Approach. Water quality monitoring of the Lagoon Pond System has been a coordinated effort between the MVC, the Towns and the Coastal Systems Program at SMAST-UMD. The water quality monitoring program was initiated in 2002 with support from the Massachusetts 604B Grant Program and continued each summer through 2007. Throughout the water quality monitoring period, sampling was undertaken between 4 and 5 times per summer during the months of June through September, the critical periods for nitrogen related water quality declines in southeastern Massachusetts estuaries. The MVC/Town based Water Quality Monitoring Program for Lagoon Pond developed baseline nutrient related water quality data for 7 sampling stations distributed throughout the Eastern Arm (branch) and the tributary West Arm as well as sampling of water flowing out of Upper Lagoon Pond (Figure II-1). As remediation plans for this and other various systems on Martha's Vineyard are implemented throughout the Towns, monitoring will have to be resumed or continued to provide quantitative information to the Towns relative to the efficacy of remediation efforts.

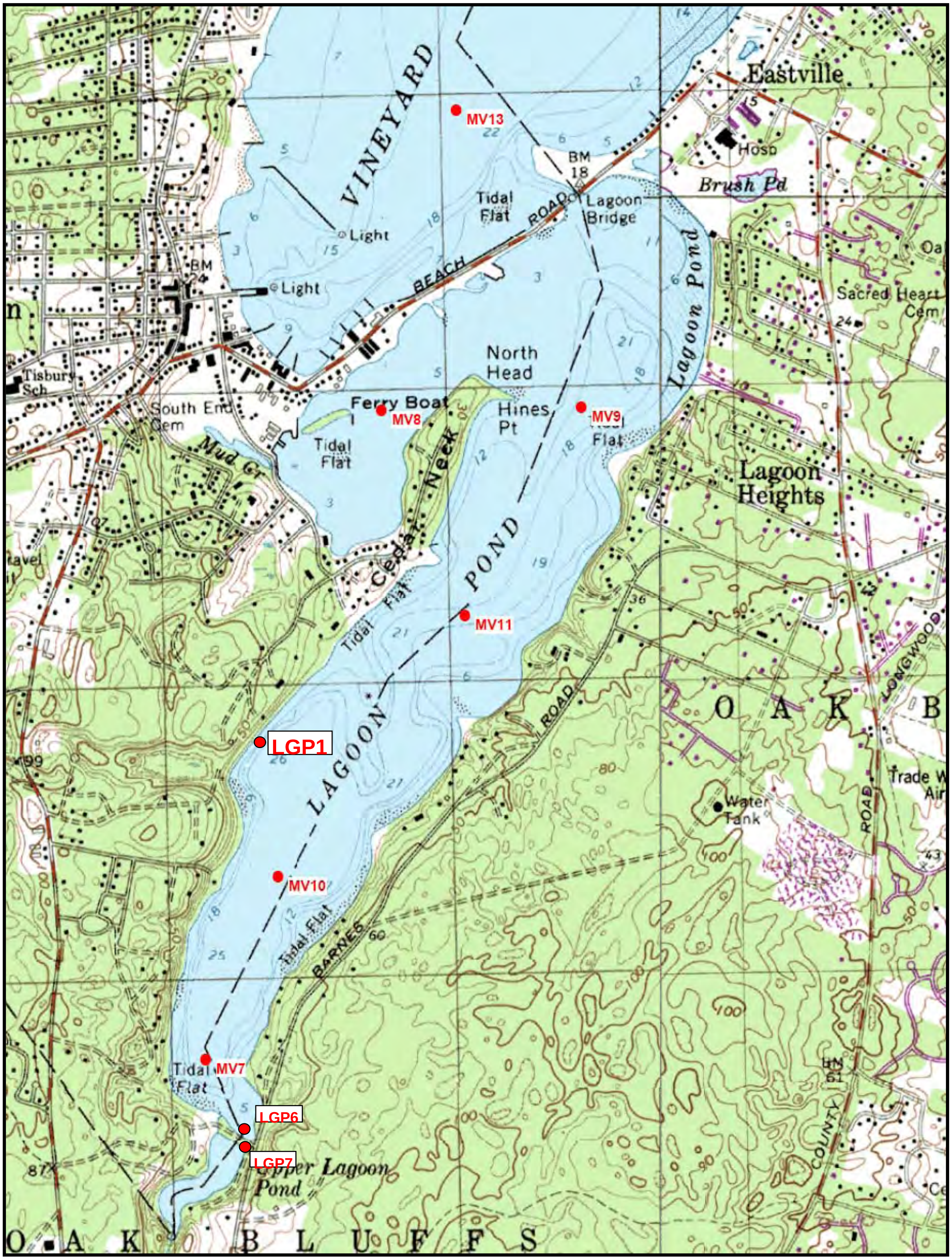


Figure II-1. MVC/Town of Oak Bluffs/Town of Tisbury Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the MVC/SMAST/Town and volunteers. Stream water quality stations depicted in Chapter 4 sampled weekly by the MEP.

Regulatory Assessments of Lagoon Pond Resources - The Lagoon Pond Estuary contains a variety of natural resources of value to the citizens of Oak Bluffs and Tisbury as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP gathers the available information on these resources as part of its assessment, and presents them here (Figures II-2 through II-5) for reference by those providing stewardship for this estuary. For the Lagoon Pond Estuary these include:

- Mouth of River designation – MassDEP (not applicable for Lagoon Pond system)
- Designated Shellfish Growing Area – MassDMF (Figure II-2)
- Shellfish Suitability Areas - MassDMF (Figure II-3)
- Anadromous Fish Runs - MassDMF (Figure II-4)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-5)

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 Lagoon Pond Estuarine System. The MEP has incorporated all appropriate data from previous studies to enhance the development of nitrogen thresholds for the Lagoon Pond System and to reduce costs of restoration for the Towns of Oak Bluffs and Tisbury.

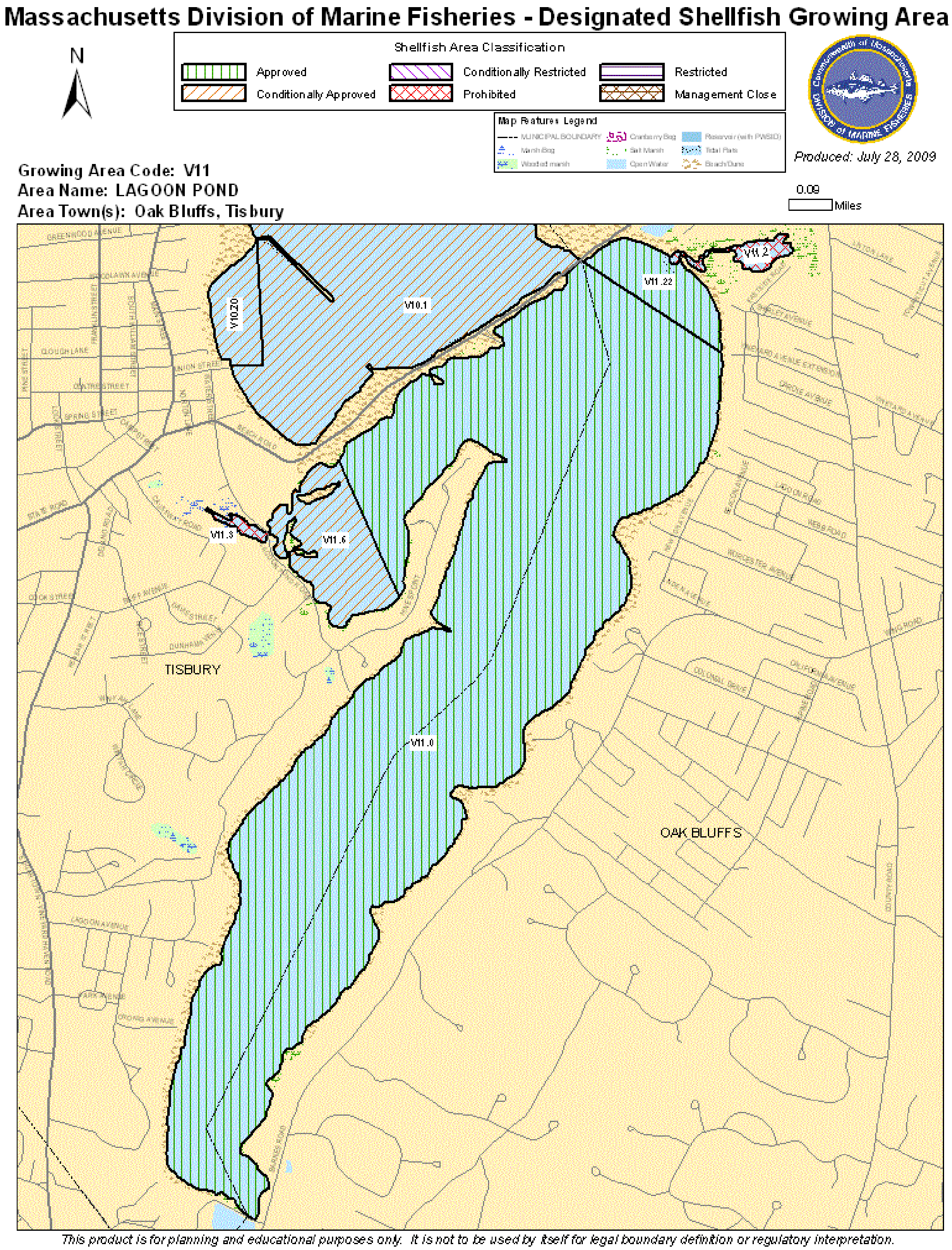


Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

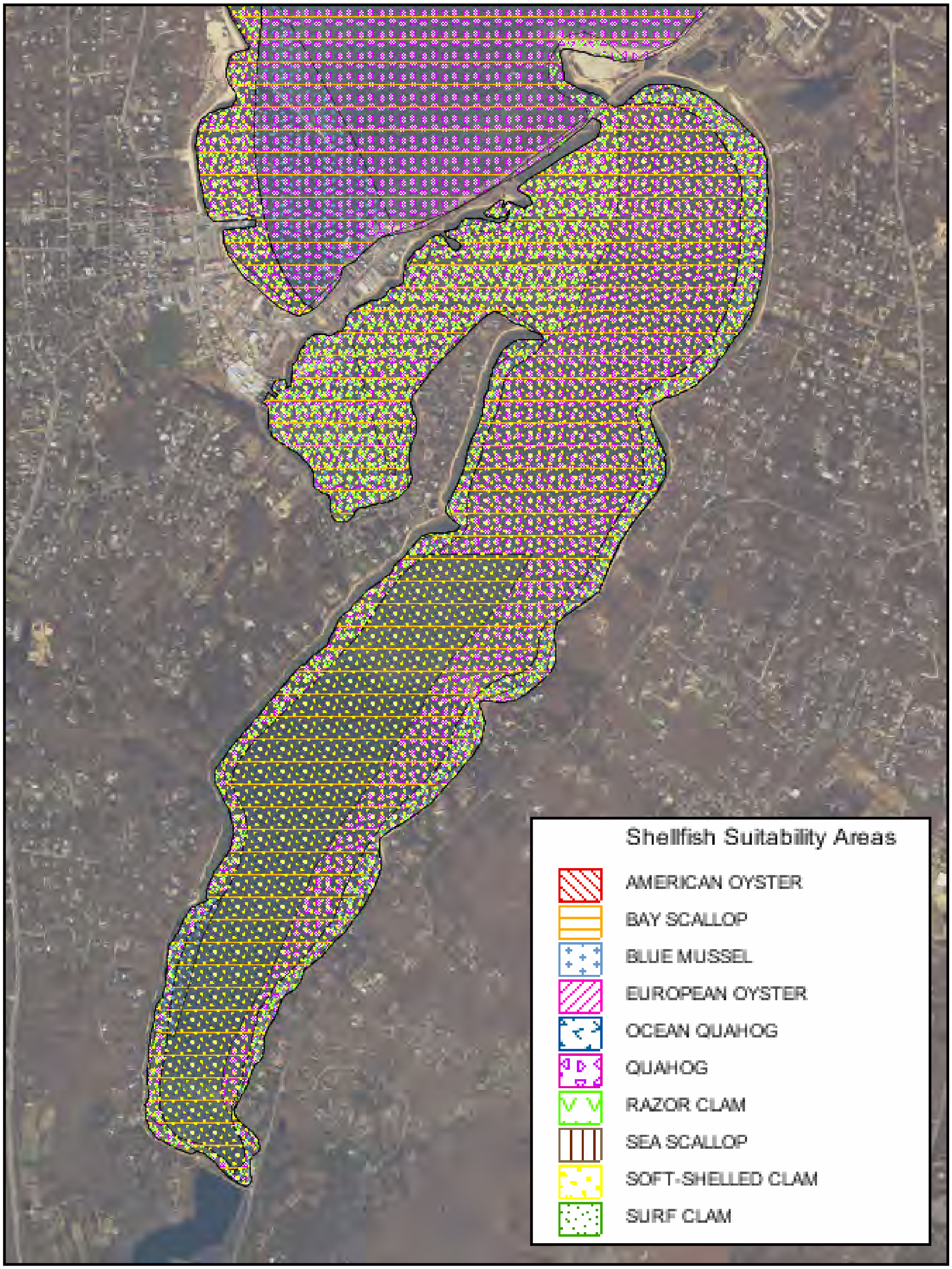


Figure II-3. Location of shellfish suitability areas within the Lagoon Pond Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

Figure II-4. Anadromous fish runs within the Lagoon Pond Estuary as determined by Mass Division of Marine Fisheries. The red diamonds show areas where fish were observed. The uppermost sites are within a freshwater pond, Upper Lagoon Pond, which is connected by a fish run to the estuarine portion of Lagoon Pond. The run represents a surface water pathway for nutrients to enter the Lagoon Pond System.

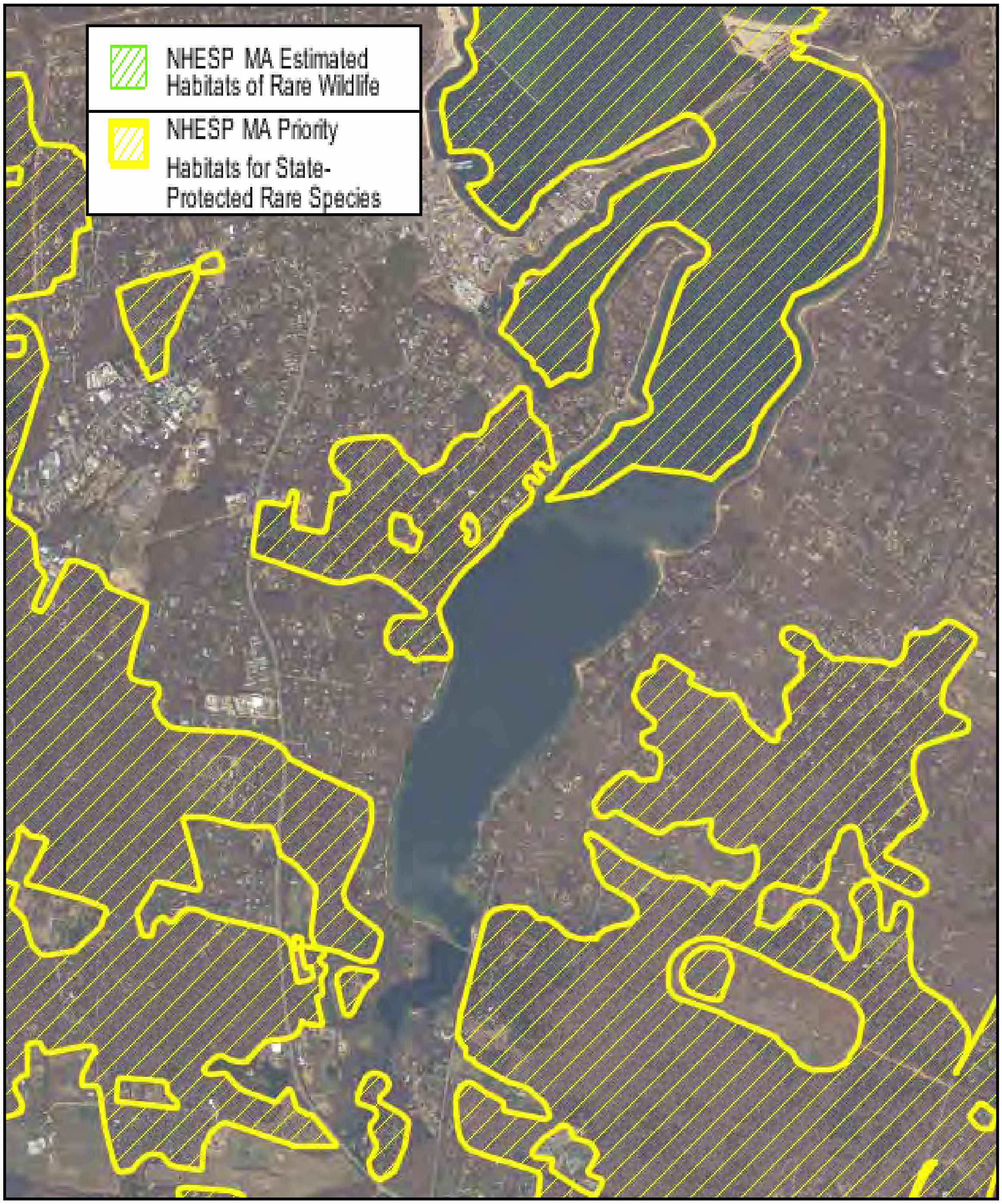


Figure II-5. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Lagoon Pond Estuary as determined by - NHESP.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

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

The relatively porous deposits that comprise most of the Vineyard outwash plain and the eastern moraine create a hydrologic environment nearly completely lacking significant streams and where watershed boundaries are usually better defined by elevation of the groundwater and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). Freshwater discharge to estuaries is usually composed of surface water inflow from streams, which receive much of their water from groundwater base flow, and direct groundwater discharge. For a given estuary, differentiating between these two water inputs and tracking the sources of nitrogen that they carry requires determination of the portion of the watershed that contributes directly to a stream and the portion of the groundwater system that discharges directly into an estuary as groundwater seepage. In the Lagoon Pond watershed, freshwater directly discharges from Upper Lagoon Pond with the remainder of the freshwater watershed inputs to the estuary via direct groundwater.

Lagoon Pond and its watershed are mostly located within the eastern moraine with the westernmost portions of the watershed within the upper portions of the outwash plain. The groundwater system in the eastern moraine has generally been characterized as approximately as permeable as the outwash plain and the 1977 United States Geological Survey (USGS) regional water table map shows northern groundwater flow lines from the western moraine toward the eastern coast that seem uninfluenced by the moraine (Delaney, 1980). It should also be noted based on Delaney, 1980 that public supply well pump tests and modeling produced Zone 2 areas that were largely unaffected by the geology of the two areas. In 1991, the USGS developed another regional water table map, which generally showed the same water table contours (Masterson and Barlow, 1996). Masterson and Barlow constructed a regional two-dimensional, finite-difference flow model that could be used to calculate drawdowns in groundwater levels due to pumping of public water supply wells, but could not be calibrated against actual water level readings. These USGS characterizations of the geology, including the installation of numerous long-term monitoring wells, over the last few decades have provided the basis for subsequent activities, including the delineation of estuary watersheds. In 1994, Whitman and Howard produced a groundwater model with a domain that covered Martha's Vineyard eastern moraine and the outwash plain; this model was based on the publicly available USGS MODFLOW three-dimensional, finite difference groundwater model code. In 1999, Earth Tech updated the 1994 Whitman and Howard regional model and used an associated model to conduct groundwater particle tracking analysis. In 2002, the MVC defined all of the coastal pond watersheds based primarily on the 1994 Whitman and Howard groundwater model output of long term groundwater elevation contours, a survey of groundwater table elevations within the Tisbury Great Pond and Edgartown Great Pond watersheds carried out by MVC and other sources of information. For those systems outside of the outwash plain aquifer, surface elevation contours were used to estimate the watershed divides.

Since the initial analysis, the groundwater model (revised/updated EarthTech model with USGS guidance) was used to refine individual watershed boundaries within the outwash plain geologic unit as each pond system is readied for its watershed land use loading model. These revisions have been done as a collaborative effort between MVC, USGS and MEP staff.

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

III.2 LAGOON POND CONTRIBUTORY AREAS

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

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

MEP staff utilized the Lagoon Pond watershed to develop daily discharge volumes for various sub-watersheds as calculated from the watershed areas and an island-specific recharge rate. In order to develop the groundwater discharge volumes, MEP staff determined a recharge rate of 28.7 inches per year for Martha's Vineyard. This recharge rate estimate was largely based on review of the relationship between recharge and precipitation rates used on Cape Cod. In the preparation of the Cape Cod groundwater models, the USGS used a recharge rate of 27.25 in/yr for calibration of the groundwater models to match measured water levels (Walter and Whealan, 2005). The Cape Cod recharge rate is 61% of the estimated 44.5 in/yr of precipitation on the Cape. Precipitation data collected by the National Weather Service at Edgartown since 1947 has an average over the last 20 years of 46.9 in/yr (http://www.mass.gov/dcr/waterSupply/rainfall/precipdb.htm). If the Cape Cod relationship between precipitation and recharge is applied to the average Martha's Vineyard precipitation rate, the estimated recharge rate on Martha's Vineyard is 28.7 in/yr. This rate was used to estimate groundwater flow to Lagoon Pond and its various subwatersheds (Table III-1). The discharge volumes developed for the subwatersheds were used to assist in the salinity calibration of the tidal hydrodynamic models. The overall estimated groundwater flow into Lagoon Pond from the MEP delineated watershed is 31,529 m3/d. This flow includes inflow through the spillway from Upper Lagoon Pond. Given the model grid refinements completed by the MEP Technical Team, led in this effort by USGS staff, MEP Technical Team staff are highly confident that the delineation in Figure III-1 is accurate and an appropriate basis for completion of the linked watershed-embayment model for Lagoon Pond.

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

Watershed	Watershed #	Watershed Area (acres)	Discharge	
			m^3/day	ft^3/day
Lagoon Pond	1	2,894	23,393	826,110
Upper Lagoon Pond	2	794	6,516	230,123
West Arm	3	200	1,620	57,201
TOTAL		3,889	31,529	1,113,434

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

The MEP watershed delineation is at least the fifth watershed delineation completed for the Lagoon Pond System. Figure III-2 compares the delineations completed under selected past efforts with the current project delineation. Most of the previous watershed delineations relied on the groundwater contour map created by the USGS (Delaney, 1980) with modifications based on measured streamflow (Poole, 1999) or salinity balance (Gaines, 1986). Watershed areas ranged from 3,336 to 4,868 acres. The most recent MVC delineation had a watershed area of 4,406 acres including 538 acres for the surface of Lagoon Pond (MVC, 2000). The MEP watershed area for the Lagoon Pond system as approximately the same as the MVC (2000) area if the estuary surface area (573 acres) is included: total MEP area = 4,462 acres. The MEP area delineation also includes interior sub-watersheds to West Arm and Upper Lagoon Pond that have generally not been included in previous delineations.

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

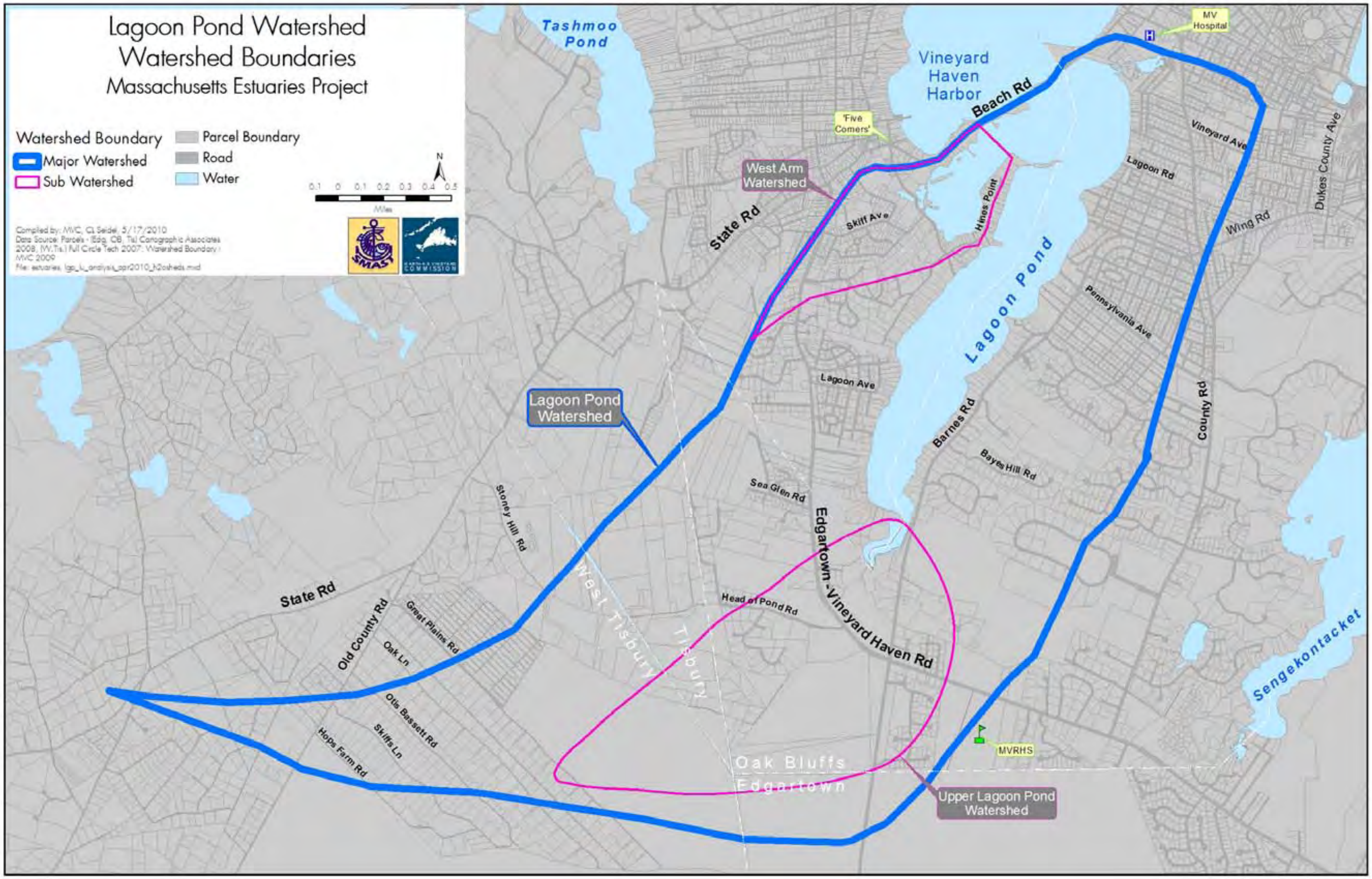


Figure III-1. Watershed and sub-watershed delineations for the Lagoon Pond estuary system. Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI).

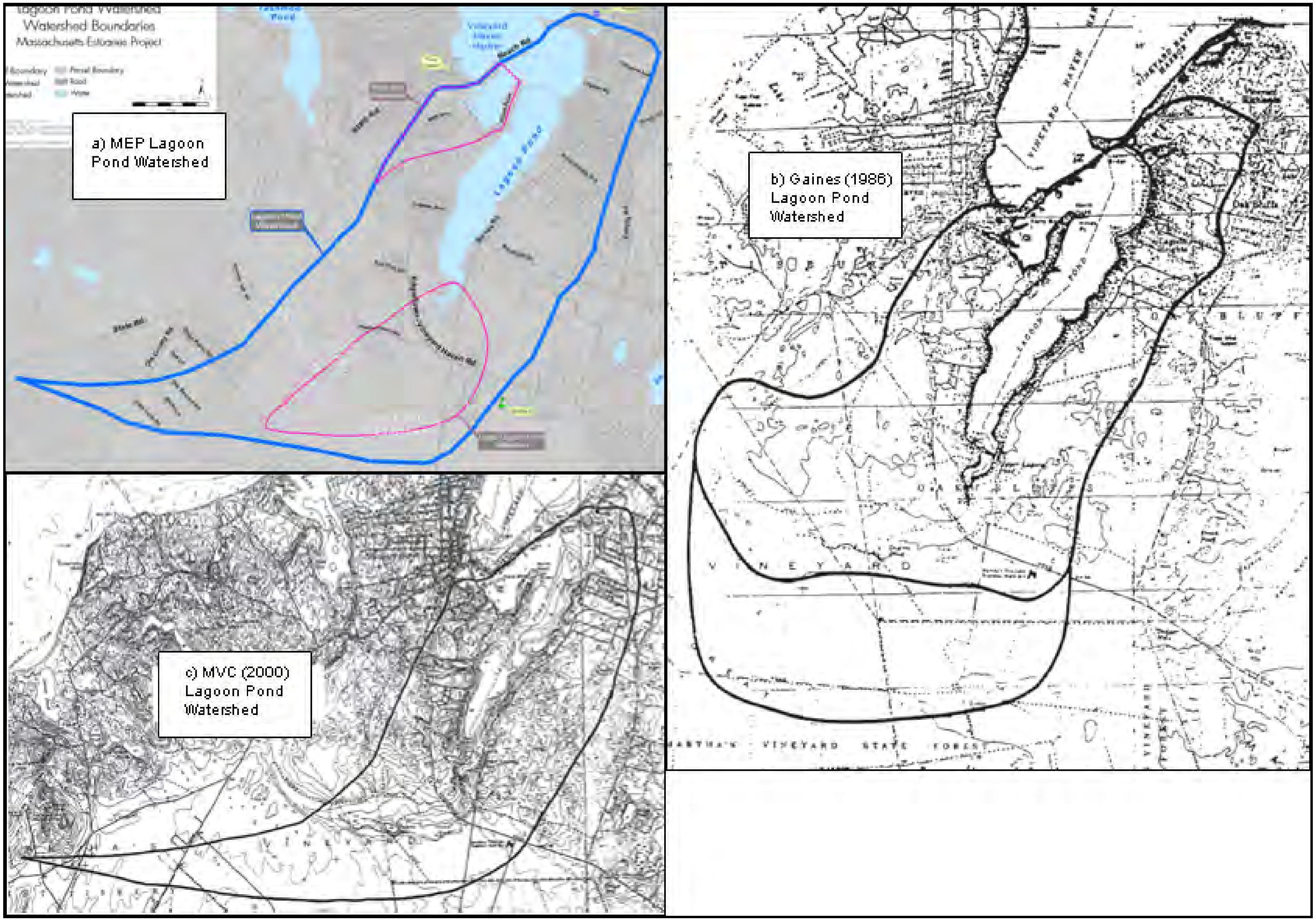


Figure III-2. Comparison of MEP watershed and sub-watershed delineations used in the current analysis (a) with selected historic delineations: b) Gaines (1986) and c) MVC (2000).

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

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

The MEP Technical Team worked with the Martha's Vineyard Commission (MVC) staff in a coordinated manner to develop the watershed nitrogen loads to the Lagoon Pond estuary. This effort led to the identification of watershed nitrogen sources and the development of nitrogen-loading rates (Section IV.1) from the watershed to the tidal waters of Lagoon Pond (Section III). The Lagoon Pond watershed is divided into three sub-watersheds; one to the main portion of Lagoon Pond, one for West Arm, and another for Upper Lagoon Pond (see Chapter III).

Determination of the nitrogen loads required obtaining watershed specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. Loading from land-uses also required individual lot-by-lot data and were also derived from other in-depth studies (such as the stream gaging program, Section IV-2) for different portions of the watershed. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Module based upon sub-watershed-specific land uses and associated nitrogen loading rates. For the Lagoon Pond System, MVC-supplied land-use data were transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as water use data provided by the Oak Bluffs Water District and the Tisbury Water Works). The resulting nitrogen loads represent the "potential" or unattenuated nitrogen load to the receiving estuarine waters, since attenuation during transport through streams or freshwater ponds has not yet been included.

Natural attenuation of watershed nitrogen during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. Stream flow was characterized at the "stream" discharging from Upper Lagoon Pond. A sub-watershed to this point is functionally the same as the recharge area to Upper Lagoon and allows comparison between field collected data from the stream and pond and estimates from the nitrogen-loading sub-model. The watershed to Lagoon Pond contains other, smaller aquatic features that do not have separate watersheds delineated and, thus they are not explicitly included in the watershed analysis. If these small features were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (~10%) overestimated given the distribution of nitrogen sources and these features within the watershed. Stream flow and associated surface water attenuation is included in the MEP's nitrogen attenuation and freshwater flow investigation, presented in Section IV.2. The MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the other two sub-watersheds that directly discharge groundwater to the estuary.

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

IV.1.1 Land Use and Water Use Database Preparation

Martha's Vineyard Commission (MVC) staff, with direction from Estuaries Project staff, combined digital parcel and tax assessors data from the MVC Geographic Information Systems Department for the four towns in the Lagoon Pond watershed: Oak Bluffs, Edgartown, Tisbury, and West Tisbury. Digital parcels and land use/assessors data for Oak Bluffs, Edgartown, and Tisbury are from 2008, while the West Tisbury data are from 2007. These land use databases contain traditional information regarding land use classifications (MADOR, 2008) plus additional information developed by the MVC.

Figure IV-1 shows the land uses within the Lagoon Pond Estuary watershed area. Land uses in the study area are grouped into nine land use categories: 1) residential, 2) commercial, 3) industrial, 4) agricultural, 5) mixed use, 6) undeveloped (including residential open space), 6) public service/government, including road rights-of-way, 8) freshwater ponds, and 9) unclassified properties. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2008). "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (e.g., wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges. Unclassified parcels are properties without any assessor land use classifications.

In the overall Lagoon Pond watershed, the predominant land use based on area is residential properties, which account for 38% of the overall watershed area; public service/government properties have the second highest percentage of the system watershed (34%) (Figure IV-2). When the number of parcels in the watershed are considered, 72% of the

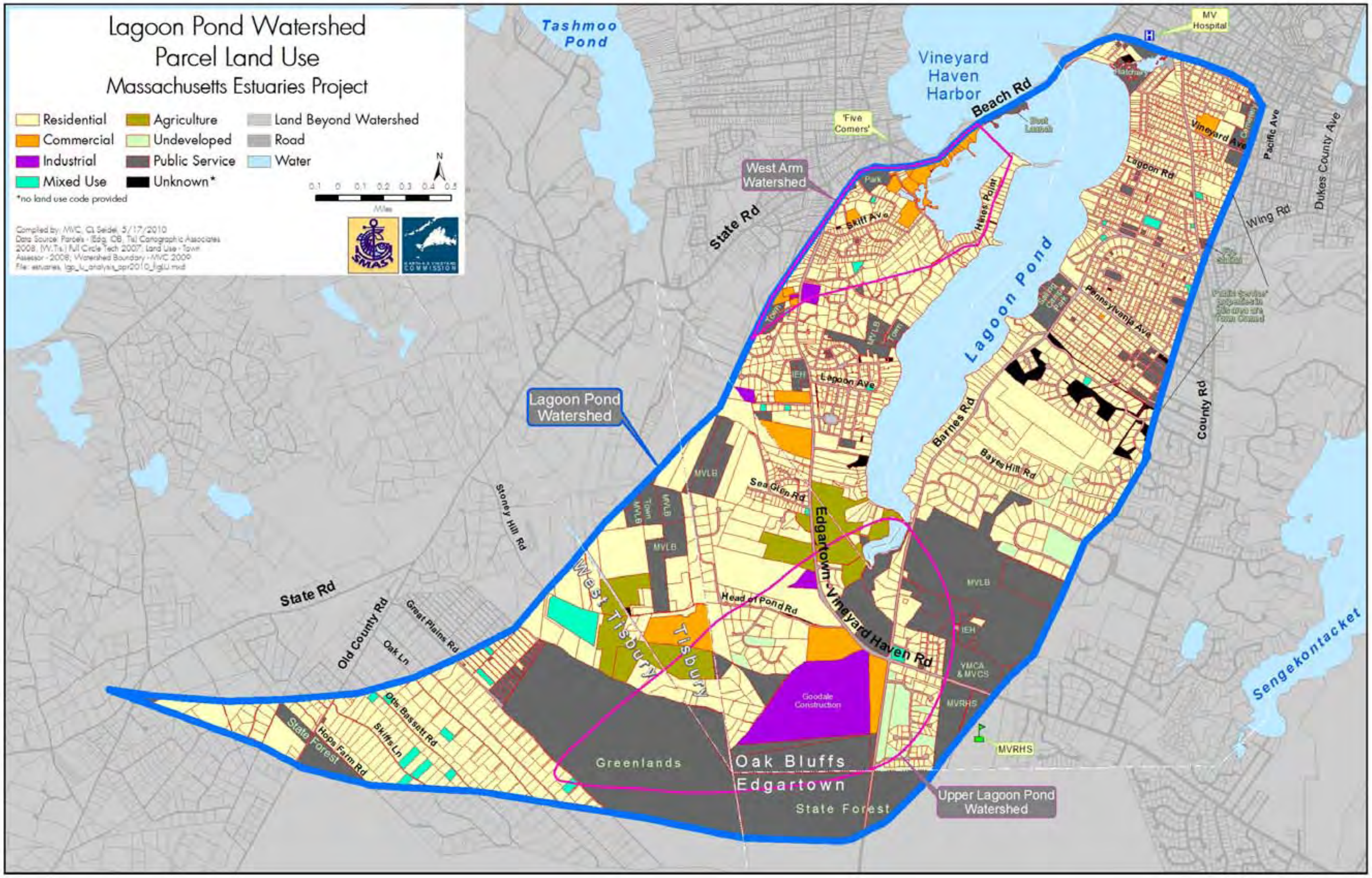


Figure IV-1. Land-use in the Lagoon Pond watershed. The watershed is primarily within the Towns of Oak Bluffs and Tisbury with small portions within the Town of Edgartown and West Tisbury. Land use classifications are based on assessors' records provided by the town.

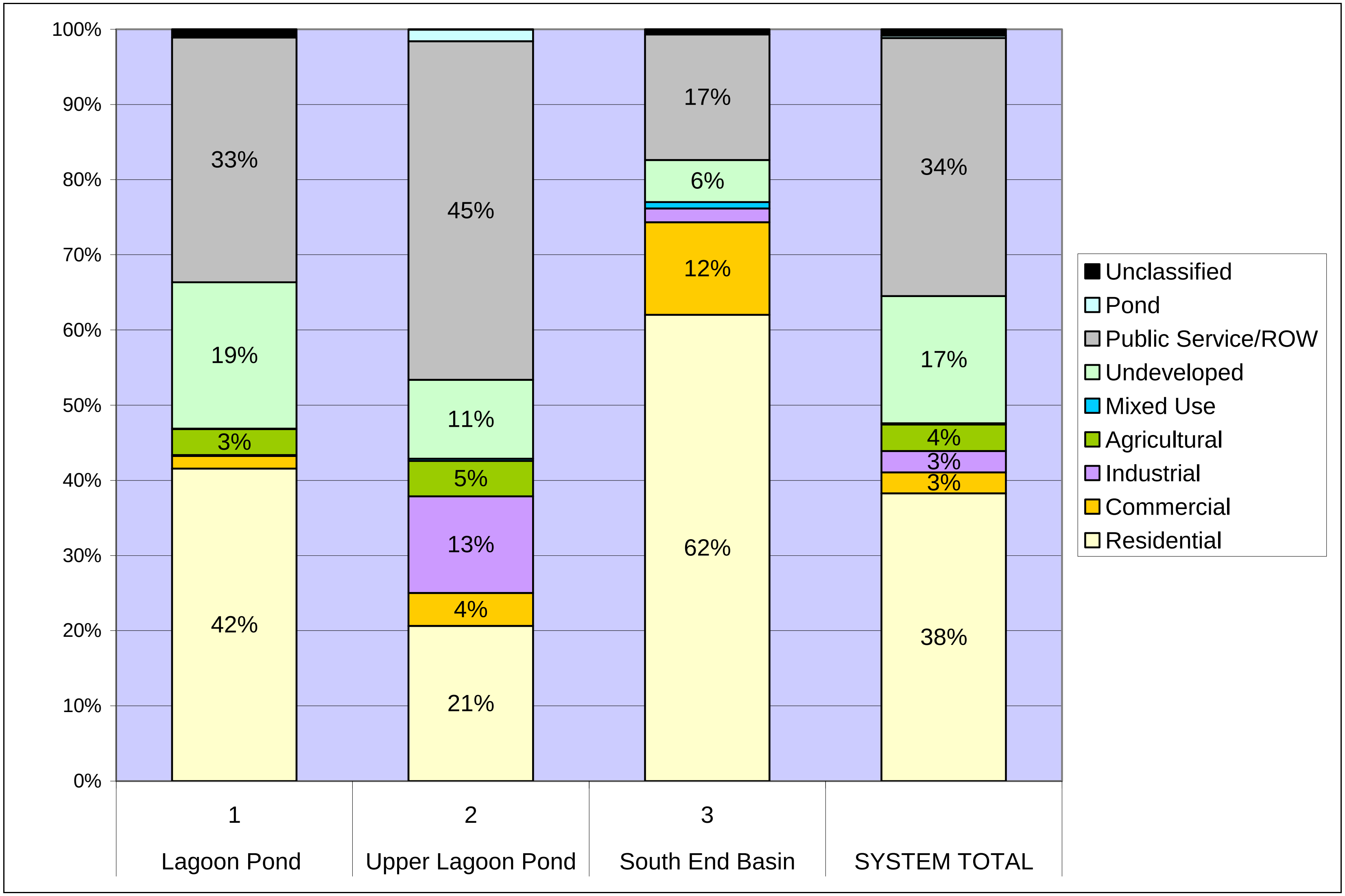


Figure IV-2. Distribution of land-uses within the sub-watersheds and the entire watershed to Lagoon Pond. Land use categories are generally based on assessor's land use grouping recommended by MADOR (2008). Only percentages greater than or equal to 3% are shown.

parcels in the system watershed are classified as residential with undeveloped parcels accounting for the second highest percentage (18%). Single-family residences (MADOR land use code 101) are 87% of the residential parcels and 83% of the residential land area. Residential land uses are the dominant land use category based on area in two of the individual sub-watersheds (Lagoon and West Arm {SouthEnd Basin}); public service/government is the dominant land use (45% of the area) in the Upper Lagoon Pond sub-watershed. Undeveloped parcels are the third highest land use area classification in the overall watershed and in the Lagoon Pond sub-watershed. Commercial land uses are the third highest (12%) in the West Arm (South End Basin) sub-watershed, while industrial land uses are the third highest (13%) in the Upper Lagoon Pond sub-watershed. Overall, undeveloped land uses account for 17% of the entire Lagoon Pond system watershed area, while agricultural properties account for the next highest percentage (4%) following residential, public service, and undeveloped.

In order to estimate wastewater flows, MEP staff generally work with municipal or water supplier partners in the study watershed to obtain parcel-by-parcel water use information. With this in mind, MVC staff contacted the Oak Bluffs Water District (OBWD) and the Tisbury Water Works and obtained average water use information for properties in and near the Lagoon Pond watershed. MVC Staff reviewed four years of water use records: 2003-2006 for Oak Bluffs and 2002 to 2005 for Tisbury. A total of 1,805 water use accounts exist in the Lagoon Pond watershed; this is 86% of the developed parcels within the watershed. The remaining 284 (14% of the total) parcels without water use or connection to sewer system were assigned water use based on averages of their respective land use code or were assigned a standard of 160 gallons per day. This standard assumption is the reported town-wide average for both Oak Bluffs and Tisbury (personal communication, Bill Wilcox, MVC). Water use from the twelve Tisbury parcels connected to the town sewer system is not included in the nitrogen loading calculations. Water use is a proxy for wastewater generation from septic systems on all developed properties in the Lagoon Pond watershed. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the average water-use, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2).

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts, decennial census data yield accurate estimates of total population only in selected watersheds. To correct for this uncertainty and more accurately assess current nitrogen loads, the MEP employs a water-use approach. The water-use approach is generally applied on a parcel-by-parcel basis within a watershed, where annual water meter data are linked to assessor's parcel information using GIS techniques. The parcel specific water use data are converted to septic system nitrogen discharges (to the receiving aquatic systems) by adjusting for consumptive use (*e.g.*, irrigation) and applying a wastewater nitrogen concentration. The water use approach focuses on the nitrogen load, which reaches the aquatic receptors down gradient 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). Down gradient studies of septic system plumes indicate that further nitrogen loss during aquifer transport is negligible (Robertson et al. 1991, DeSimone and Howes 1996).

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

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

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

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

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

In order to provide an independent validation of the average residential water use within the Lagoon Pond System watershed, MEP staff reviewed US Census population values for the four towns in the watershed. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. Based on data collected during the 2000 US Census, average occupancy within Oak Bluffs, Edgartown, West Tisbury, and Tisbury is 2.34, 2.39, 2.39, and 2.28 people per occupied housing unit, respectively. Year-round occupancy of available housing units for the four towns is 42%, 36%, 56%, and 61%, respectively. Average water use for single-family residences with municipal water accounts in the Oak Bluffs portion of MEP study area is 165 gpd and 175 gpd in the Tisbury portion. If the year-around occupancy in Oak Bluffs and Tisbury is multiplied by the state Title 5 estimate of 55 gpd per capita, the flows are 129 and 125 gpd, respectively, without correction for seasonal use.

Estimates of summer populations on Cape Cod and Martha's Vineyard derived from a number of approaches (*e.g.*, traffic counts, garbage generation, WWTF flows) generally suggest average population increases from two to three times year-round residential populations measured by the US Census. If it is assumed that seasonal properties, 58% and 39% of the residential units in Oak Bluffs and Tisbury, respectively, according to the 2000 Census, are occupied at twice the year-round occupancy for three months, the estimated average water use for Oak Bluffs would be 161 gpd, while if the seasonal properties are occupied at three times the year-round occupancy for three months, the estimated average water use for Tisbury would be 188 gpd. Both of these results approximate the water use averages for single family residences in the respective towns.

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 gaging actual occupancy in areas impacted by seasonal population fluctuations such as most of Cape Cod, Martha's Vineyard, and Nantucket. The above analysis reinforces the difficulty in relying on population estimates, while also providing some confirmation that water use, on average, is a reasonable estimate of wastewater generation within the study area.

Water use information exists for 86% of the developed parcels in the Lagoon Pond watershed. The remaining 14% of the developed parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (*e.g.*, 101 or 325), have been confirmed as having buildings on them through a review of aerial photographs, and/or do not have a listed account in the water use databases. Of the 284 developed parcels without water use accounts, 229 (81%) are classified as single-family residences (land use code 101). Of these single-family residences, 88% of them are in the Lagoon Pond sub-watershed and 69% of those are in West Tisbury. In general, these parcels are assumed to utilize private wells and are assigned an average water use for single-family residences that was developed from the average water use in the watershed and in their respective town. Assigned flows for other developed parcels are also made based on in-watershed averages for the same land use and same towns; for example multi-family residences (land use code 109) are assigned an average flow of 261 gpd in the Oak Bluffs portion of the Lagoon Pond sub-watershed and 286 gpd in the Oak Bluffs portion of the Upper Lagoon sub-watershed. In cases where land use crosses town or sub-watershed boundaries and/or does not have a large number of measured water use for the particular land use code, the parcels are assigned the watershed-wide average flow of 160 gpd.

Nitrogen Loading Input Factors: Fertilized Areas and Farming

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

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

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

In 1999, a land use survey on Martha’s Vineyard reviewed lawn sizes, including portions of the Lagoon Pond watershed (MVC, 1999). This survey found that within the Lagoon Pond watershed the average lawn size was 2,600 square feet. MVC staff re-reviewed the area of lawns in the watershed based on a review of aerial photographs and found that portions of the watershed had slightly larger lawns (3,000 sq ft) (personal communication, Bill Wilcox, MVC). In order to account for some of the uncertainty in aerial photographs, these two areas were averaged and all residential properties in the Lagoon Pond watershed are assumed to have 2,800 sq ft lawns.

The MVC (1999) survey also reviewed fertilizer application rates and found that average household fertilizer application rates averaged 1.5 lb N per 1,000 square feet of residential lawn within the Lagoon Pond watershed. MEP Technical staff reviewed these factors with MVC staff and included these factors in the development of the Lagoon Pond watershed nitrogen-loading model. MVC staff also determined individual lawn size on selected larger parcels and the area of selected parks and cemeteries based on review of aerial photographs; these site-specific areas were also included in the watershed loading model. Other factors in the model are those generally used in MEP nitrogen loading calculations.

Eleven farms also exist in the Lagoon Pond watershed; MVC staff determined the areas of greenhouse, row crops, and pasture land based on a review of aerial photographs. Nitrogen application rates for these fertilized areas are 68, 55, and 18 kg per acre, respectively. These application rates are based on standard fertilizing practices for these types of crops. Leaching rates were determined based on estimates of soil disturbance and are 10%, 33%, and 25%, respectively. Overall, farming with nitrogen fertilizers occurs on 73 acres in the Lagoon Pond system watershed and adds 845 kg per year prior to accounting for any natural attenuation in Upper Lagoon Pond.

In addition to the crops, three farms also have animals. MEP staff consulted with MVC staff to determine the number of animals on each farm. Animal types include cows, pigs, chickens, goat, sheep, and alpaca. MEP staff developed nitrogen loading rates for manure generated for each animal type based on available USDA sources and state-university extension reports. Collectively, these farm animals add 505 kg to the Lagoon Pond watershed prior to accounting for any natural attenuation in Upper Lagoon Pond. Two of the farms, which account for 92% of the unattenuated nitrogen load, are located in the sub-watershed to Upper Lagoon Pond (freshwater), which was found to attenuate some of this nitrogen prior to it reaching the estuary.

Nitrogen Loading Input Factors: Landfill

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

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

MEP staff reviewed the available and estimated inorganic nitrogen monitoring data collected since 2006 in order to better match the timeframe associated with the estuary water quality monitoring data collection. This review found that the average of the inorganic nitrogen concentration in the three monitoring wells down gradient of the landfill is 3.69 ppm, while the average concentration in the up-gradient well is 0.2 ppm. Using the difference of 3.49 ppm, the Martha's Vineyard-specific recharge rate, and the area of the landfill within the Lagoon Pond watershed, MEP staff estimated that the annual nitrogen load from the Oak Bluffs landfill to Lagoon Pond is 15 kg.

Nitrogen Loading Input Factors: Other

One of the other key factors in the nitrogen loading calculations are 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 Martha's Vineyard precipitation data and results of the USGS groundwater modeling effort on Cape Cod. Other nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the Cape Cod Commission's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and Massachusetts DEP's Nitrogen Loading Computer Model Guidance (1999). Factors used in the MEP nitrogen loading analysis for the Lagoon Pond watershed are summarized in Table IV-1.

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

Nitrogen Concentrations:	mg/l	Recharge Rates:	in/yr
Road Run-off	1.5	Impervious Surfaces	42.2
Roof Run-off	0.75	Natural and Lawn Areas	28.7
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:	
Natural Area Recharge	0.072	Existing developed residential parcels and buildout residential parcels:	Water use, land use specific average or watershed average of 160 gpd
Wastewater Coefficient	23.63		
Farmland loads based on site-specific evaluation of crops and animals			
Oak Bluffs landfill load (kg/yr) – based on site specific evaluation and portion in Lagoon Pond watershed	15	Commercial buildout additions[2]:	21 gpd /1,000 ft2 of building
Fertilizers[1]:		Commercial building coverage of developed lots and buildout additions:	28%
Average Residential Lawn Size (sq ft):	2,800	Impervious Surfaces[3]	sq ft
Residential Watershed Nitrogen Rate (lbs/1,000 sq ft)	1.5	**BUILDINGS**	1,850
		DRIVEWAYS	**1600**
		Roads	31% of right-of-way area

[1] Data from 1999 Martha's Vineyard lawn survey modified with 2003 survey results.
[2] No industrial buildout additions and only four commercial parcels with additional buildout potential
[3] building and driveway area based on Mashpee planimetric data; similar data not available for Martha's Vineyard; road area relationship based on evaluation of the Town of Harwich; road areas and widths not available for Martha's Vineyard

IV.1.3 Calculating Nitrogen Loads

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

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

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

For management purposes, the aggregated estuary watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Lagoon Pond System, the major types of nitrogen loads are: wastewater (e.g., septic systems), direct atmospheric deposition to water surfaces, impervious surfaces, agriculture, residential lawn fertilizer, and recharge on natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-3). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model.

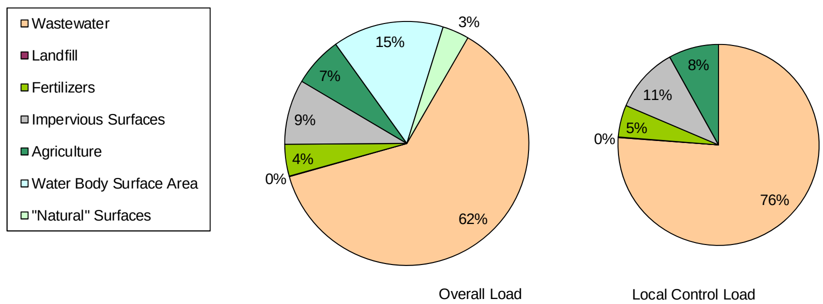
Upper Lagoon Pond Nitrogen Load

Natural nitrogen attenuation occurs in the Upper Lagoon Pond sub-watershed prior to discharge into the Lagoon Pond estuary. Upper Lagoon Pond is the only sub-watershed to a freshwater great pond in the Lagoon Pond watershed. Freshwater ponds on Martha's Vineyard are typically 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 pond water flows back into the groundwater system along the down gradient shoreline. Occasionally these ponds will also have a stream outlet or herring run that also acts as a discharge point, which is the case for Upper Lagoon flowing into the head (estuarine) of Lagoon Pond.

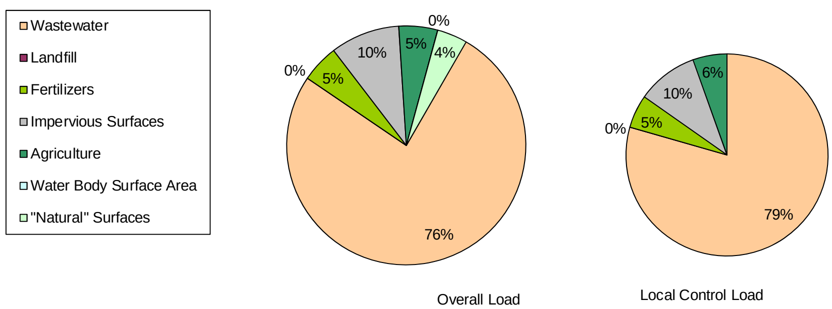
Since the nitrogen loads usually flow into a pond with the groundwater, the relatively more productive pond ecosystem incorporates some of the nitrogen, retains some nitrogen in the sediments, and changes the nitrogen among its various oxidized and reduced forms. As result of these interactions, some of the nitrogen is removed from the watershed system, mostly through burial in the sediments and denitrification that returns it to the atmosphere. Following these reductions, the remaining (attenuated) loads flow back into the groundwater system along the down gradient side of the pond or enter a stream directly with eventual discharge into the down gradient embayment. The nitrogen load summary in Table IV-2 includes both the unattenuated and attenuated nitrogen load from Upper Lagoon Pond.

Table IV-2. Lagoon Pond Nitrogen Loads. Present nitrogen loads based on current conditions including nitrogen additions from the Oak Bluffs landfill. Natural attenuation in the outflow from Upper Lagoon Pond is based on MEP stream monitoring data (Section IV-2). Buildout loads include septic, fertilizer, and impervious surface additions from developable properties. All values are kg N yr^{-1}.

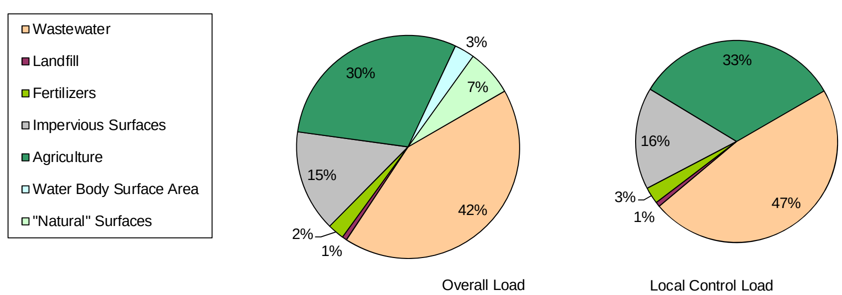
		Lagoon Pond N Loads by Input (kg/yr):								% of Pond Outflow	Present N Loads			Buildout N Loads		
Name	Watershed ID#	Wastewater	Landfill	Fertilizers	Impervious Surfaces	Agriculture	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Lagoon Pond System Total		**12748**	**15**	**862**	**1763**	**1350**	**3013**	**720**	**7010**		**20470**		**20029**	**27479**		**27010**
Lagoon Pond	1	10067		674	1240	693	0	541	6058		13216	0	13216	19275		19275
Upper Lagoon Pond	2	939	15	53	325	657	64	149	146	100%	2202	20%	1762	2348	20%	1878
South End Basin	3	1741		135	198	0	0	30	806		2103	0	2103	2909		2909
Lagoon Pond Estuary Surface							2612				2612		2612	2612		2612
South End Basin Estuary Surface							336				336		336	336		336



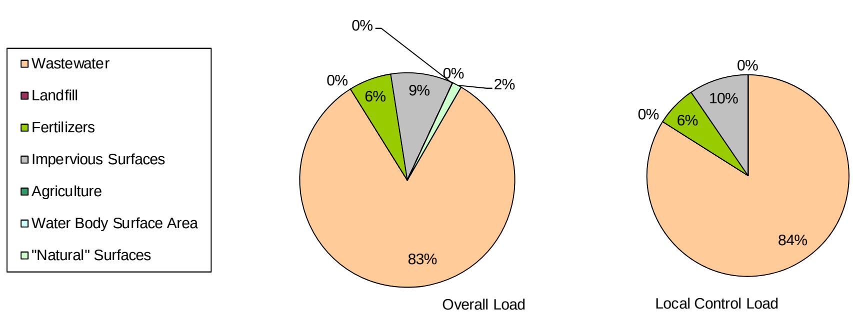
A. Lagoon Pond System TOTAL



B. Lagoon Pond subwatershed



C. Upper Lagoon Pond subwatershed



D. West Arm subwatershed

Figure IV-3. Land use-specific unattenuated nitrogen load (by percent) to the overall Lagoon Pond System watershed and subwatersheds. “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.

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 nitrogen attenuation rate different than 50% should be used for a specific pond, the MEP Technical Team reviews the available data on each pond, including available nitrogen concentrations, impacts of sediment regeneration, temperature profiles, and bathymetric information.

Bathymetric information is generally a prerequisite for determining enhanced attenuation, since it provides the volume of the pond and, with appropriate pond nitrogen concentrations, a measure of the nitrogen mass in the water column. Combined with the watershed recharge, this information can provide a residence or turnover time that is necessary to gage attenuation. In Lagoon Pond, the stream flow measurements collected by MEP match the estimated recharge volume from the watershed, which suggests that the annual watershed recharge volume flows through Lagoon Pond every year (see Section IV.2).

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

MVC staff collected available water quality monitoring data for Upper Lagoon Pond. Most of this historic data collection was relatively intermittent, although a diagnostic/feasibility study collected data over two years (1987-88) (Poole, 1986). Maximum depth measured during these years was 4.3 m, which suggests that Upper Lagoon Pond water column should be relatively well mixed with close to the same temperature throughout the water column. Limited data collection of dissolved oxygen at depth (2-3 sampling runs) show consistent anoxia which suggests that the sediments likely regenerate nutrients during the summer. Total phosphorus concentrations are excessive with concentrations ranging from approximately 40 to 90 ppb; target concentrations for Cape Cod ponds, which exist in the same EPA eco-region are approximately 10 ppb (Eichner, et al., 2003). Fortunately, MEP installed a continuous stream gage and made regular flow measurements paired with the collection of nutrient water samples at the stream outflow from Upper Lagoon Pond.

This stream flow measurement, which is discussed in greater detail in Section IV.2, established an average nitrogen load leaving Upper Lagoon Pond of 1,804 kg/yr. Given the unattenuated nitrogen load from the pond watershed of 2,202 kg/yr, this would mean that the pond is only attenuating or removing by natural processes approximately 18-20% of the load entering it. MEP staff has encountered similar low removal rates in ponds with high nitrogen loads and short residence times (e.g. Mill Pond in the Lewis Bay watershed and Mill Pond in the Three Bays watershed). Both of these ponds appear to have lost significant volume to sediment deposition. It is unclear at this point what is dampening the natural attenuation in Upper Lagoon Pond, but the collected data are clear that the natural attenuation in the pond is less than would usually be expected.

Buildout

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

The buildout procedure used in this watershed and generally completed by MEP staff is to evaluate town zoning to determine minimum lot sizes in each of the zoning districts, including overlay districts (*e.g.*, water resource protection districts). Larger lots are subdivided by the minimum lot size specified in current zoning to determine the total number of new lots. In addition, existing developed properties are reviewed for any additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence are assumed to have one additional residence at buildout. Most of the focus of new development is for properties classified as developable by the local assessor (state class land use codes 130 and 131 for residential properties). Properties classified by the various town assessors as “undevelopable” (e.g., codes 132 and 392) were not assigned any development at buildout. Commercially developable properties were not subdivided; the area of each parcel and the factors in Table IV-1 were used to determine a wastewater flow for these properties. Based on the buildout assessment completed for this review, there are 1,011 potential additional residential dwellings, 253 additional guesthouse additions, and 196,765 square feet of developable commercial land in the Lagoon Pond system watershed. Most (87%) of the additional residential parcels and guesthouse additions are in the Lagoon Pond subwatershed; only 29 additional residential parcels (3% of the total) are indicated in the Upper Lagoon Pond subwatershed. All the parcels included in the buildout assessment of the overall Lagoon Pond system watershed are shown in Figure IV-4.

Table IV-2 also presents a sum of the additional nitrogen loads by subwatershed for the buildout scenario. This sum includes the wastewater, fertilizer, and impervious surface loads from additional residential dwellings added, as well as wastewater and impervious surface loads from projected commercial buildout additions. Overall, buildout additions within the Lagoon Pond system watershed will increase the unattenuated loading rate by 34%.

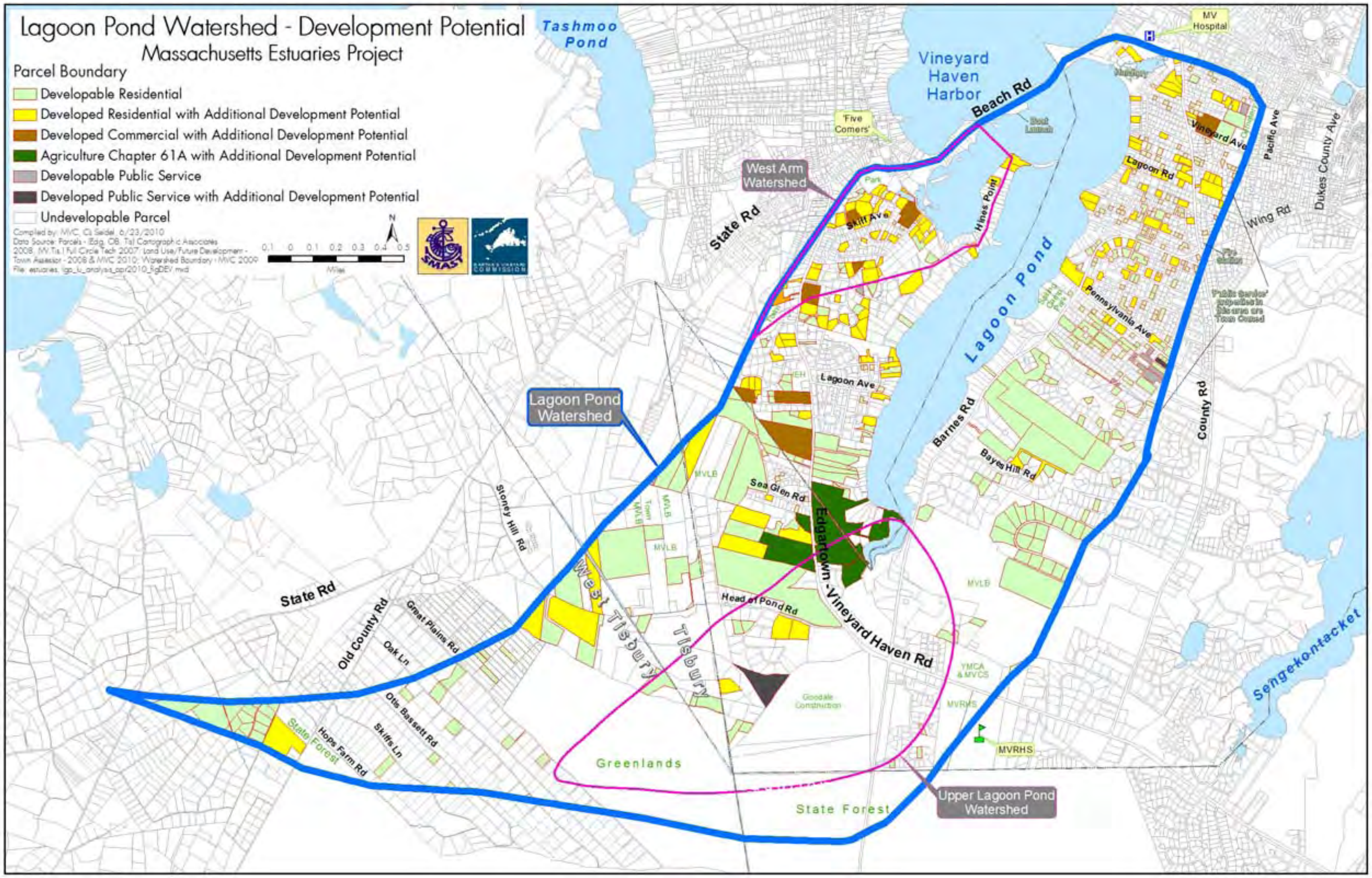


Figure IV-4. Developable Parcels in the Lagoon Pond watershed. Parcels classified by the town assessors as developable and developed parcels with additional development potential based on zoning are shown. Nitrogen loads in the buildout scenario are based on additional development assigned to these parcels.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

IV.2.1 Background and Purpose

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. 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 estuarine systems. Rates of nitrogen loading to the sub-watersheds of the Lagoon Pond System being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1).

If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such as the developed regions of the Lagoon Pond 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 Lagoon Pond embayment system, a portion of the watershed derived freshwater flow and transported nitrogen passes through a surface water system prior to discharging to the headwaters of the Lagoon Pond Estuary. The surface water system consists of Upper Lagoon Pond (a great freshwater pond) with its fringing wetlands, and surface water discharge via a fish ladder (for anadromous fish passage, Chapter 2) directly flowing into estuarine waters. This surface freshwater system provides the potential for nitrogen removal (attenuation) as nitrogen moves though the pond on its way to the sea.

Failure to determine the attenuation of watershed derived nitrogen overestimates the nitrogen load to receiving estuarine waters. If nitrogen attenuation is significant in one portion of a watershed and insignificant in another the result is that nitrogen management would likely be more effective in achieving water quality improvements if focused on the watershed region having unattenuated nitrogen transport (other factors being equal). In addition to attenuation by freshwater ponds (see Section IV.1.3, above), attenuation in surface water flows is also important. An example of the significance of surface water nitrogen attenuation relating to embayment nitrogen management was seen in the Agawam River, where >50% of nitrogen originating within the upper watershed was attenuated prior to discharge to the Wareham River Estuary (CDM 2000). Similarly, MEP analysis of the Quashnet River indicates that in the upland watershed, which has natural attenuation predominantly associated with riverine processes, the integrated attenuation was 39% (Howes et al. 2004). In addition, 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 Approach in the Lagoon Pond embayment system. MEP conducted long-term measurements of natural attenuation relating to Upper Lagoon Pond and its discharge with additional measures of other surface water features in the watershed such as fresh kettle ponds (Section IV.1). The Upper Lagoon Pond sampling and analysis was conducted at the fish ladder (Figure IV-5). While it is not a typical stream outflow, it is the location where freshwater flows can 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 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 gaging sites. Flow and nitrogen load were measured at the gage in the freshwater “stream” site for a total of 18 months of record (Figures IV-6). During the study period, velocity profiles were completed in the fish ladder 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 flow out of the Upper Pond via the fish ladder at the gage 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 Lagoon Pond 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 Upper Lagoon Pond to the estuarine reach of Lagoon Pond.

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

Periodic measurement of flows over the entire gage 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 gage 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 Lagoon Pond embayment system from Upper Lagoon Pond.

The annual flow record for the surface water flow at the gage was merged with the nutrient data set generated through the weekly water quality sampling performed at the gage location to determine nitrogen loading rates to the head of the Lagoon system. 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 gaging site. For the gage 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 samples were not collected thus creating a gap in the water quality data set at the Lagoon Pond gage. It was therefore necessary to utilize average water quality concentrations for those months in 2004 paired with flows from 2003 in order to calculate an estimate of nutrient load for a complete year. While this is not typically the way the MEP determines nutrient loads, it is assumed that since there is little change in the watershed land use from one year to the next, the nutrient concentrations from one year should generally be representative of the nutrient concentration in the previous or next year. 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 gaged "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 Upper Lagoon Pond to Estuarine Reach of Lagoon Pond

Upper Lagoon Pond, located at the head of the Lagoon Pond Estuary, is an artificially created freshwater pond with a surface water discharge via a fish ladder to the estuary. A MEP stream gage 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 Upper Lagoon Pond above the gage site and the measured annual discharge of nitrogen to the tidal portion of the Lagoon Pond system, Figure IV-5.

At the Lagoon Pond gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the freshwater portion of the fish ladder connecting Upper Lagoon Pond to the estuarine reach of Lagoon Pond. This fish ladder carries the flows and associated nitrogen load to the Lagoon Pond Estuary, which then flushes to Vineyard Haven Harbor and the near shore waters of Vineyard Sound. As the lower portion of the fish ladder is tidally influenced, the gage was located as best as possible in the fish ladder taking into consideration the up-gradient constraints of the structure as well as accessibility. Ultimately, the gage 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 gage 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 gage location was deemed acceptable for making freshwater flow measurements. Calibration of the gage was checked approximately monthly. The gage in the fish ladder from Upper Lagoon 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 Lagoon Pond site based upon these flow measurements and measured water levels at the gage 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 Lagoon Pond system while being reflective of the biological processes occurring in Upper Lagoon 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 gage site.

The annual freshwater flow record for the fish ladder discharging from Upper Lagoon Pond 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 0.8% 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 6,464 m^3/day was virtually the same as the long term average flows determined from a water balance of the delineated Upper Long Pond watershed (equivalent to inflow to the pond) of 6,516 m3/day. While there may be some seepage under the rock and rubble berm that forms Upper Lagoon 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 ~130 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 of 6,464 m3/d versus 6,516 m3/d, respectively.

Table IV-3. Comparison of water flow and nitrogen load discharged by the fish ladder (freshwater "stream") connecting Upper Lagoon Pond to the estuarine reach (head) of the Lagoon Pond system. The "Stream" data are from the MEP stream gaging 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 Upper Lagoon Pond	Data Source
Total Days of Record	365[(b)]	(1)
Flow Characteristics		
Stream Average Discharge (m3/day)	6,464	(1)
Contributing Area Average Discharge (m3/day)	6,516	(2)
Discharge Stream 2003-04 vs. Long-term Discharge	0.8%	
Nitrogen Characteristics		
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.157	(1)
Stream Average Total N Concentration (mg N/L)	0.765	(1)
Nitrate + Nitrite as Percent of Total N (%)	21%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	4.94	(1)
TN Average Contributing UN-attenuated Load (kg/day)	6.03	(3)
Attenuation of Nitrogen in Pond/Stream (%)	18%	(4)

(a) Flow and N load to fish ladder discharging from Upper Lagoon Pond to the estuarine reach of Lagoon Pond, 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 Lagoon Pond; and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates.
(4) Calculated based upon the measured TN discharge from the "stream" vs. the unattenuated watershed load.

Table IV-4. Summary of annual volumetric discharge and nitrogen load from the fish Ladder discharge from Upper Lagoon Pond to the estuarine reach of Lagoon Pond (head of Lagoon Pond estuarine system) based upon the data presented in Figures IV-6 and Table IV-3.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Fish Ladder (Upper Lagoon Pond) Upper Lagoon Pond Discharge (MEP)	**September 1, 2003 to August 31, 2004**	**2,359,165**	**371**	**1804**
Fish Ladder (Upper Lagoon Pond) Upper Lagoon Pond Discharge (CCC)	Based on Watershed Area and Recharge	**2,378,340**	--	--

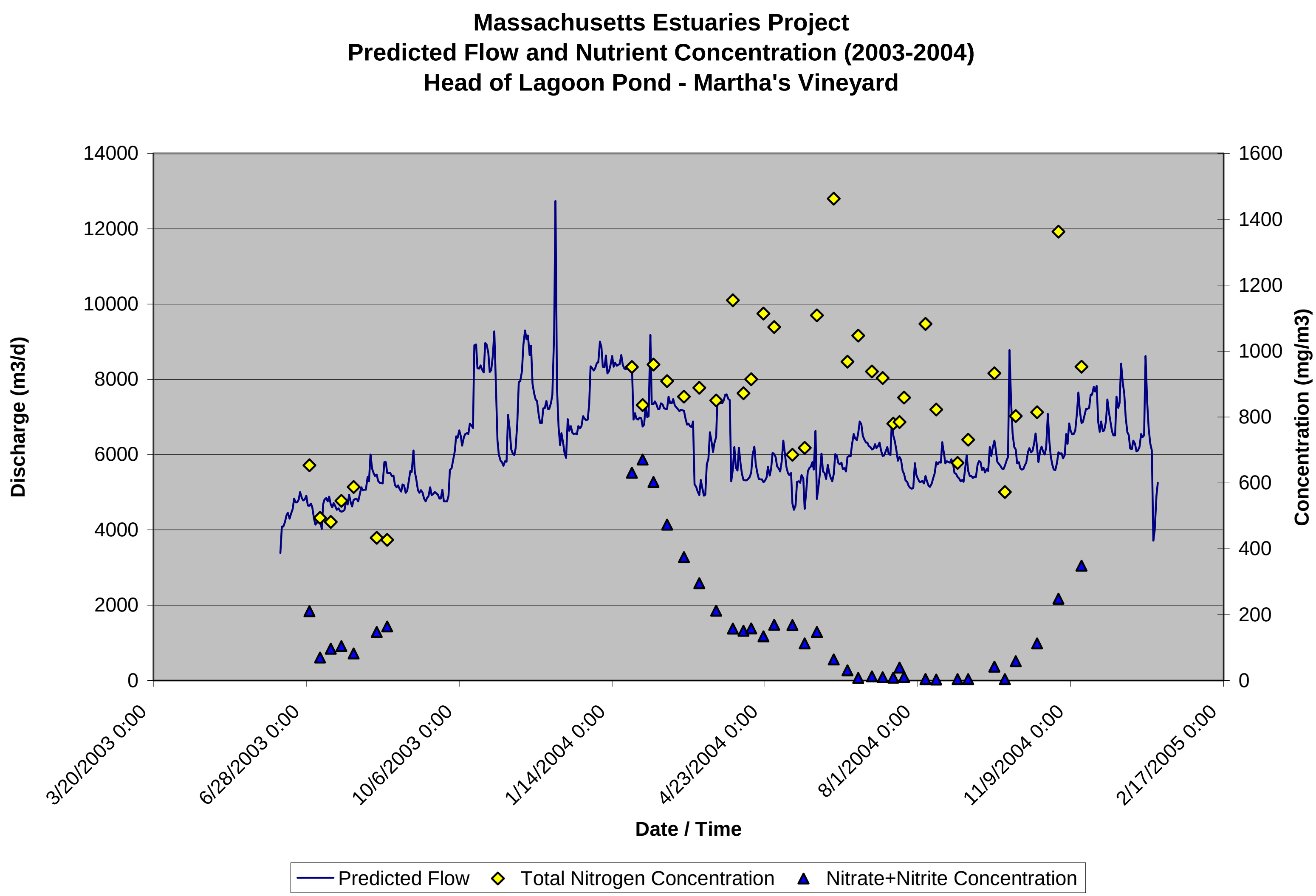


Figure IV-6. Upper Lagoon Pond discharge (solid blue line), nitrate+nitrite (blue triangle) and total nitrogen (yellow square) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Lagoon Pond (Table IV-4). Gap in concentration (8/21/03 to 1/26/04) due to lack of samples. Average concentrations for same months in 2004 utilized to estimate annual load.

Even so, the MEP did a sensitivity analysis on the potential error associated with a large unobserved seepage. If accounting for seepage would raise the measured outflow by 10% (7110 versus 6464 m3/d) the result would be an increase in TN discharge of ~180 kgN/yr. This increase in TN discharge would increase the N load to the eastern arm of Lagoon Pond by ~1% of the watershed + atmospheric deposition N load. This is a very small potential error. However, if this level of missed flow were occurring it would be ~650 m3/d and should be observable at low tide, particularly since most seepage would occur during the low tide period (due to hydraulic gradient). The excellent 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 to Upper Lagoon Pond is properly delineated.

Total nitrogen concentrations within the outflow from Upper Lagoon Pond were low to moderate, averaging 0.765 mg N L^{-1}. Combining the measured flow and nitrogen levels yielded an average daily total nitrogen discharge to the estuary of 4.94 kg/day and a measured total annual TN load of 1,804 kg/yr. In the freshwater flowing out of Upper Lagoon Pond through the fish ladder, nitrate made up significantly less than half of the total nitrogen pool (21%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was taken up by plants within Upper Lagoon Pond or other natural processes occurring in the watershed. Given the low level of remaining nitrate in the “stream” discharge, the possibility for additional nitrogen removal by direct denitrification is low. However, the particulate nitrogen loss from Upper Lagoon Pond to the estuary is relatively high, with concentrations averaging 0.223 mg N L^{-1}. As a result, approaches which would retain particulate organic matter within the freshwater system and sediments could significantly increase natural attenuation and may warrant further investigation. At present, it is not possible to give specific recommendations for enhancing particulate retention in Upper Lagoon Pond, as sufficient site-specific data are not available for a feasibility study. Scientists from the Coastal Systems Program-SMAST have examined mechanisms to enhance retention in other systems and in general, modifications to pond depth or enhancement of fringing marshes that increase residence time or denitrification capacity should be examined as a mechanism for dealing with particulate organic nitrogen. Raising water levels against an earthen dam is generally not the first approach, unless levels are lower today than historically. That being said, it appears that load reductions necessary to meet nutrient concentration thresholds in Lagoon Pond will be required and that any potential enhancement of natural attenuation in this surface water system will in itself be insufficient to restore the estuary.

From the measured nitrogen load discharged by Upper Lagoon Pond to the Lagoon Pond 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. Based upon lower total nitrogen load (1,804 kg yr^{-1}) discharged from the freshwater fish ladder compared to that added by the various land-uses to the associated watershed (2,202 kg yr^{-1}), the integrated attenuation in passage through ponds in the watershed prior to discharge to the estuary is 18% (i.e. 18% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other freshwater systems evaluated under the MEP is expected given the lack of up-gradient ponds in the watershed that would be capable of attenuating nitrogen. The directly measured nitrogen load from the “stream” was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

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 Lagoon Pond embayment system. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh 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 Lagoon Pond 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 Nantucket Sound). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom sediments. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with associated nitrogen “load” become incorporated into the surficial sediments of the system.

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

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, such as found 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 West Arm (South End Basin) and the deeper embayment basins in the East Arm of Lagoon Pond 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 Lagoon Pond embayment system, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected from a total of 16 sites in the Lagoon Pond system. Cores were collected from 3 sites within the West Arm, 5 sites in the upper portion of the main Lagoon Pond basin (East Arm-South Basin), 4 sites in the middle portion of the East Arm (Central Basin) of Lagoon Pond and 4 sites from the lower portion of the East Arm (North Basin) closest to the inlet to Vineyard Haven Harbor (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:

Lagoon Pond Benthic Nutrient Regeneration Cores

- LGP-1 1 core (West Arm or South End Basin)
- LGP-2 1 core (West Arm or South End Basin)
- LGP-3 1 core (West Arm or South End Basin)
- LGP-4 1 core (East Arm Lower-North Basin)
- LGP-5 1 core (East Arm Lower-North Basin)
- LGP-6 1 core (East Arm-Central Basin)
- LGP-7 1 core (East Arm Lower-North Basin)
- LGP-8 1 core (East Arm Lower-North Basin)
- LGP-9 1 core (East Arm Mid-Central Basin)
- LGP -10 1 core (East Arm Mid-Central Basin)
- LGP -11 1 core (East Arm Upper-South Basin)
- LGP -12 1 core (East Arm Upper-South Basin)
- LGP -13 1 core (East Arm Upper-South Basin)
- LGP -14 1 core (East Arm Upper-South Basin)
- LGP -15 1 core (East Arm Upper-South Basin)
- LGP -16 1 core (East Arm Mid-Central Basin)

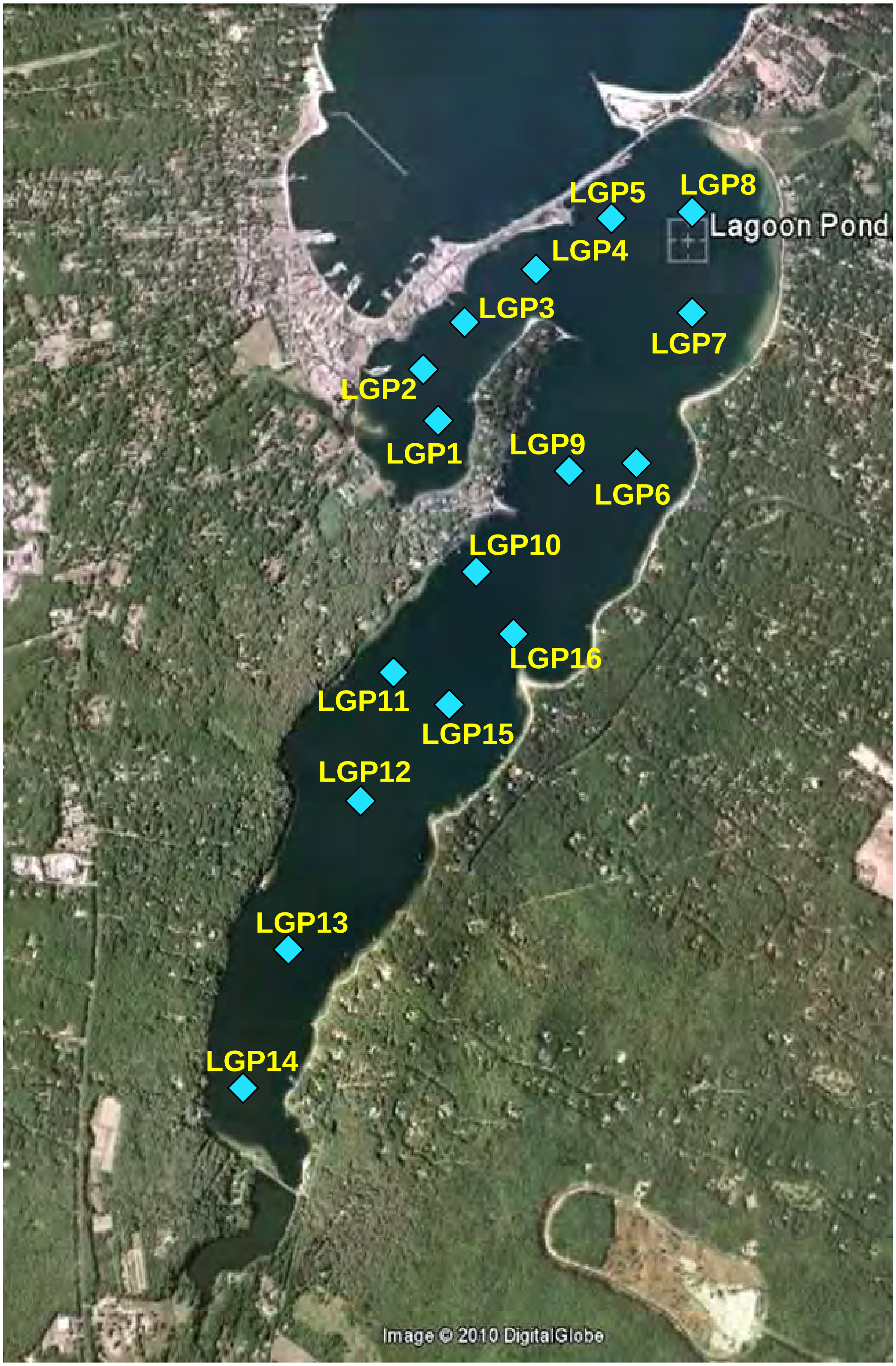


Figure IV-7. Lagoon Pond embayment system sediment sampling sites (blue symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above.

Sampling was distributed throughout the primary component basins of the Lagoon Pond 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 d1white@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), and uptake (e.g. photosynthesis). As stated above, during the warmer summer months the sediments of shallow embayments typically act as a net source of nitrogen to the overlying waters and help to stimulate eutrophication in organic rich systems. However, some sediments may be net sinks for nitrogen and some may be in "balance" (organic N particle settling = nitrogen release). Sediments may also take up dissolved nitrate directly from the water column and convert it to dinitrogen gas (termed "denitrification"), hence effectively removing it from the ecosystem. This process is typically a small component of sediment denitrification in embayment sediments, since the water column nitrogen pool is typically dominated by organic forms of nitrogen, with very low nitrate concentrations. However, this process can be very effective in removing nitrogen loads in some systems, particularly in streams, ponds and salt marshes, where overlying waters support high nitrate levels. In estuarine sediments most denitrification in sediments occurs as settled organic particles decompose and released ammonium is oxidized to nitrate. Some of this nitrate "escapes" to the overlying water and some is denitrified within the sediment column. Both pathways of denitrification are at work within the Lagoon Pond System.

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

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

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

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

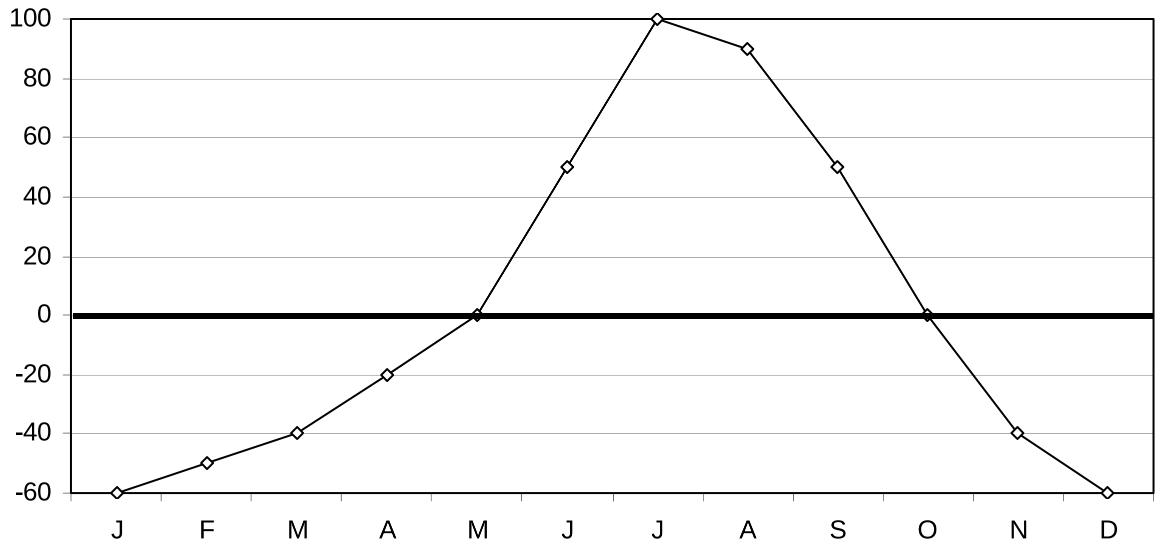


Figure IV-8 Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (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 Lagoon Pond 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 of the East Arm and the enclosed basin of the West Arm supporting the highest rates of release and diminishing rates in basins 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 (Chapter 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 areas, as opposed to tidal rivers with extensive tidal salt marsh areas. Overall, the rates of net nitrogen release were low to moderate, 8.4 - 45.2 mg m^{-2} d^{-1}, 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}; Cotuit Bay, -29.1 mg m^{-2} d^{-1}). Also, the upper tributary basins to Great and Bournes Ponds (Falmouth, MA) and Green Pond, which are structured similarly to the East Arm of Lagoon Pond, support similar net nitrogen release rates of 56.5-100.7 mg m^{-2} d^{-1}, 29.3 - 51.5 mg m^{-2} d^{-1} and 12.9 - 54.5 mg m^{-2} d^{-1}, respectively. In addition estuaries not associated with Nantucket/Vineyard Sound also have rates consistent with the basin type of Lagoon Pond, The River within Pleasant Bay supporting rates of 12.0 - 34.2 mg N m^{-2} d^{-1}.

Net nitrogen release rates for use in the water quality modeling effort for the main basins of the Lagoon Pond system (Chapter VI) are presented in Table IV-5. There was a clear spatial pattern of sediment nitrogen flux, with net uptake of nitrogen within the upper reach of the East Arm and the enclosed basin of the West Arm (South End Basin) receiving most of the watershed nitrogen discharge and having the highest water column nitrogen and highest sediment release of nitrogen. The lower reaches of the East Arm ranged from low net release to a small uptake in the basin nearest the tidal inlet. The sediments within the Lagoon Pond Estuary showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to this system and its relatively high flushing rate.

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

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			Station ID *
	Mean	S.E.	# sites	
Lagoon Pond Estuarine System				
East Arm – South (Upper)	45.2	22.0	5	LGP-11,12,13,14,15
East Arm – Central (Mid)	8.4	27.2	4	LGP-6,9,10,16
East Arm - North (Lower)	-2.3	16.4	4	LGP-4,5,7,8
West Arm - South End Basin	31.8	40.0	3	LGP-1,2,3

* 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 Lagoon Pond estuary system (Figure V-1). For this system, the final calibrated model offers an understanding of water movement through the estuary, and provides the first step towards evaluating water quality, as well as tool for later determining nitrogen loading “thresholds”. Tidal flushing information is utilized as the basis for a quantitative evaluation of water quality. Nutrient loading data combined with measured environmental parameters within the various sub-embayments become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing estuarine water quality, as well as determining the likely positive impacts of various alternatives for improving overall estuarine health, enabling the bordering towns (Oak Bluffs and Tisbury) 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 Lagoon Pond system, the most important parameters are the tide range along with the shape, length and depth of the estuary.

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

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

The Lagoon Pond estuary (Figure V-1) is a tidally dominated embayment system open to Vineyard Haven Harbor and Vineyard Sound. Lagoon Pond has two main sub-embayments: the West Arm (South End Basin) and Brush Pond. The West Arm (South End Basin) of Lagoon Pond is mostly shallow sub-embayment (with a mean depth of -3 ft NGVD) situated near the pond inlet, along the Beach Road causeway. Brush Pond is a marsh system with an area coverage of approximately 16.6 acres. The total length of the estuarine reach of main basin of the system is approximately 2.3 miles (12,100 ft), and it has a mean depth of -12 ft NGVD. The greatest depths in the entire system exist in a deep basin located in the southern half of the Pond. Average depths for the deeper southern half are -19 ft, with maximum depths at -28 ft NGVD.

Since the water elevation difference between Vineyard Haven Harbor and the inland reaches of Lagoon Pond 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 flushed efficiently. Any issues with water quality, therefore, would likely be due other factors including nutrient loading conditions from the system's watersheds, and the small tide range in Vineyard Sound.

Circulation in Lagoon Pond 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 Haven Harbor at a gage station installed on the Vineyard Haven Yacht Club pier, and also at three stations located within the estuary. All temperature-depth recorders (TDRs or tide gages) were installed for a 40-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 various sub-embayments was evaluated accurately.

V.2 FIELD DATA COLLECTION AND ANALYSIS

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

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

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

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

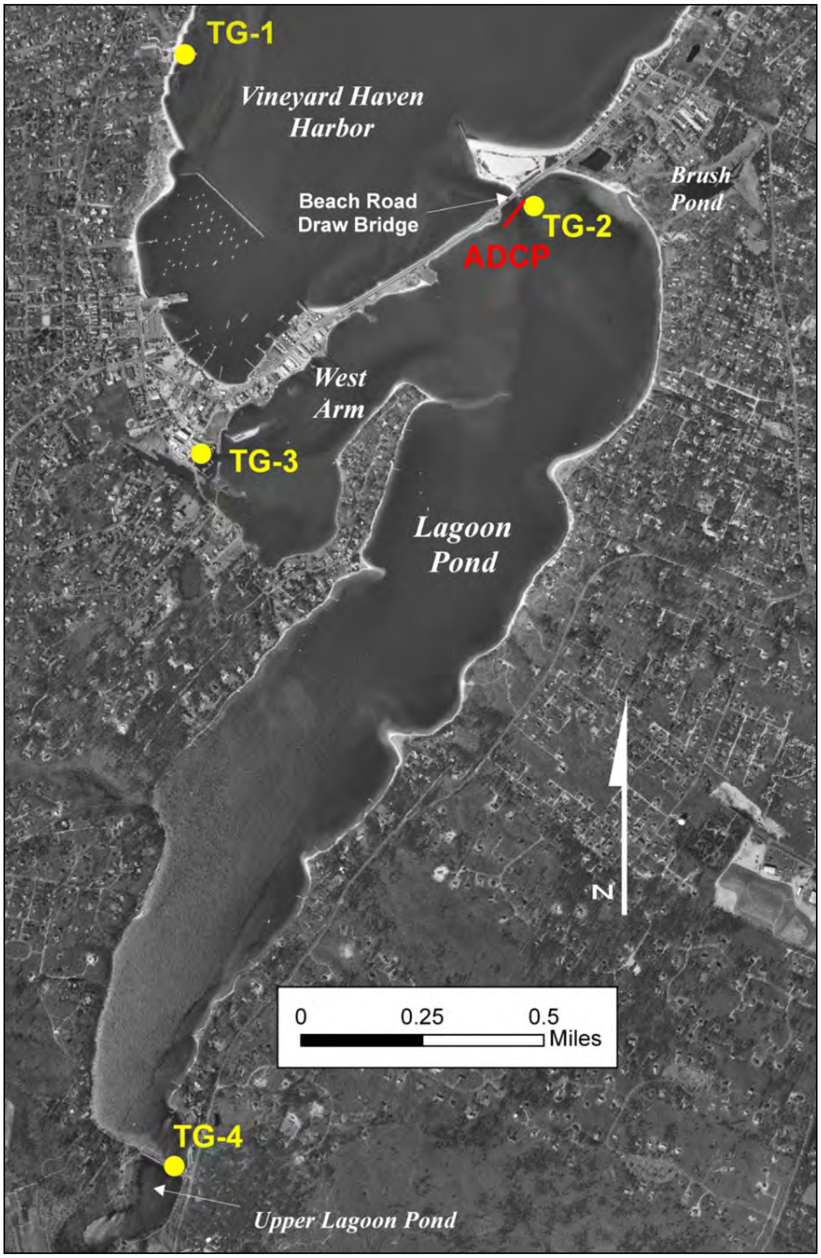


Figure V-2. Map of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. Four (4) gauges were deployed for the 40-day period between May 6 and June 15, 2004. Each yellow dot represents the approximate locations of the tide gauges: (TG-1) at the Vineyard Haven Yacht Club (Offshore), (TG-2) in northern Lagoon Pond at the drawbridge, (TG-3) in the West Arm (South End Basin) of Lagoon Pond at Meicel Marine, (TG-4) at the head and southern extent of Lagoon Pond.

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 Lagoon Pond. The survey was performed to determine flow rates at the inlet at discreet times during the course of a full tide cycle.

V.2.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Lagoon Pond 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 Haven Harbor that were not covered by the more recent survey.

The hydrographic survey of May, 2004 (CRE, 2004) was designed to cover the entire basin of Lagoon Pond, along with the West Arm (South End Basin) and portions of Vineyard Haven Harbor. Survey transects were densest in the vicinity of the inlet, were 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 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

Variations in water surface elevation were measured at three locations in the Lagoon Pond, and at a single station in Vineyard Haven Harbor. Stations within the Lagoon Pond were located at the inlet (TG-2), at Maciel Marine in the West Arm (South End Basin) (TG-3), southern limit of the Pond (TG-4), near the fish ladder to Upper Lagoon Pond. Temperature-Depth Recorders (TDRs) were deployed at each gauging station in early May 2004, and recovered in mid June, 2004. The duration of the TDR deployment allowed time to conduct the ADCP and bathymetric surveys, as well as sufficient data to perform a thorough analysis of the tides in the system.

The tide records from Lagoon Pond were corrected for atmospheric pressure variations and then rectified to the NGVD 29 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 32-day period of the TDR deployment.

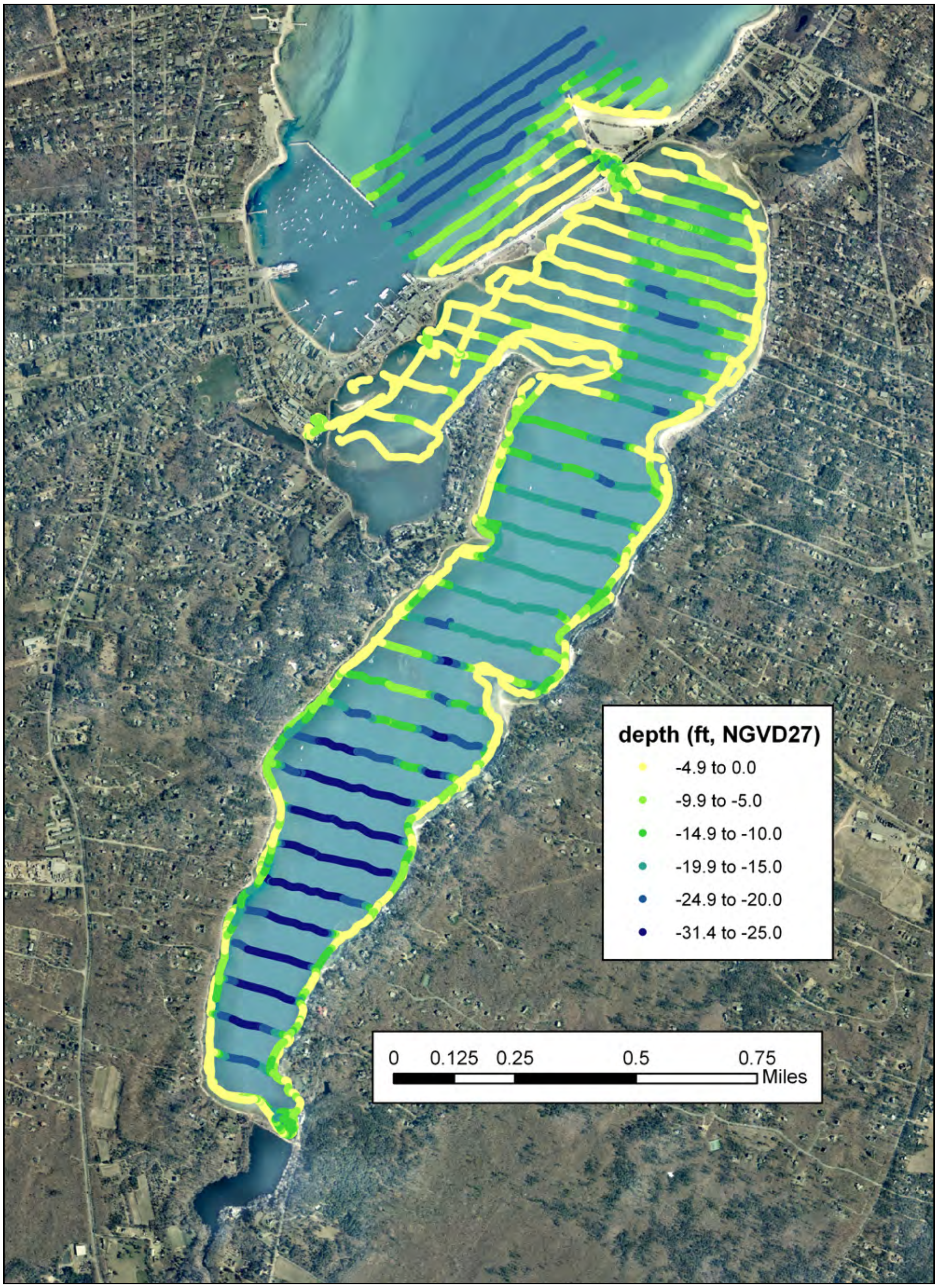


Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

Tide records longer than 29 days are necessary for a complete evaluation of tidal dynamics within the estuarine system. Although a one-month record likely does not include extreme high or low tides, it does provide an accurate basis for typical tidal conditions governed by both lunar and solar motion. For numerical modeling of hydrodynamics, the typical tide conditions associated with a one-month record are appropriate for driving tidal flows within the estuarine system.

The loss of amplitude together with increasing phase delay with increasing distance from the inlet 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 Lagoon Pond, a visual comparison in Figure V-5 between tide elevations at the three stations along the system demonstrates how little change there is between the tide range and timing from Vineyard Haven Harbor to the farthest inland reach of the Pond. This provides an initial indication that flushing conditions in the Pond are ideal, with minimal loss of tidal energy along the length of the system.

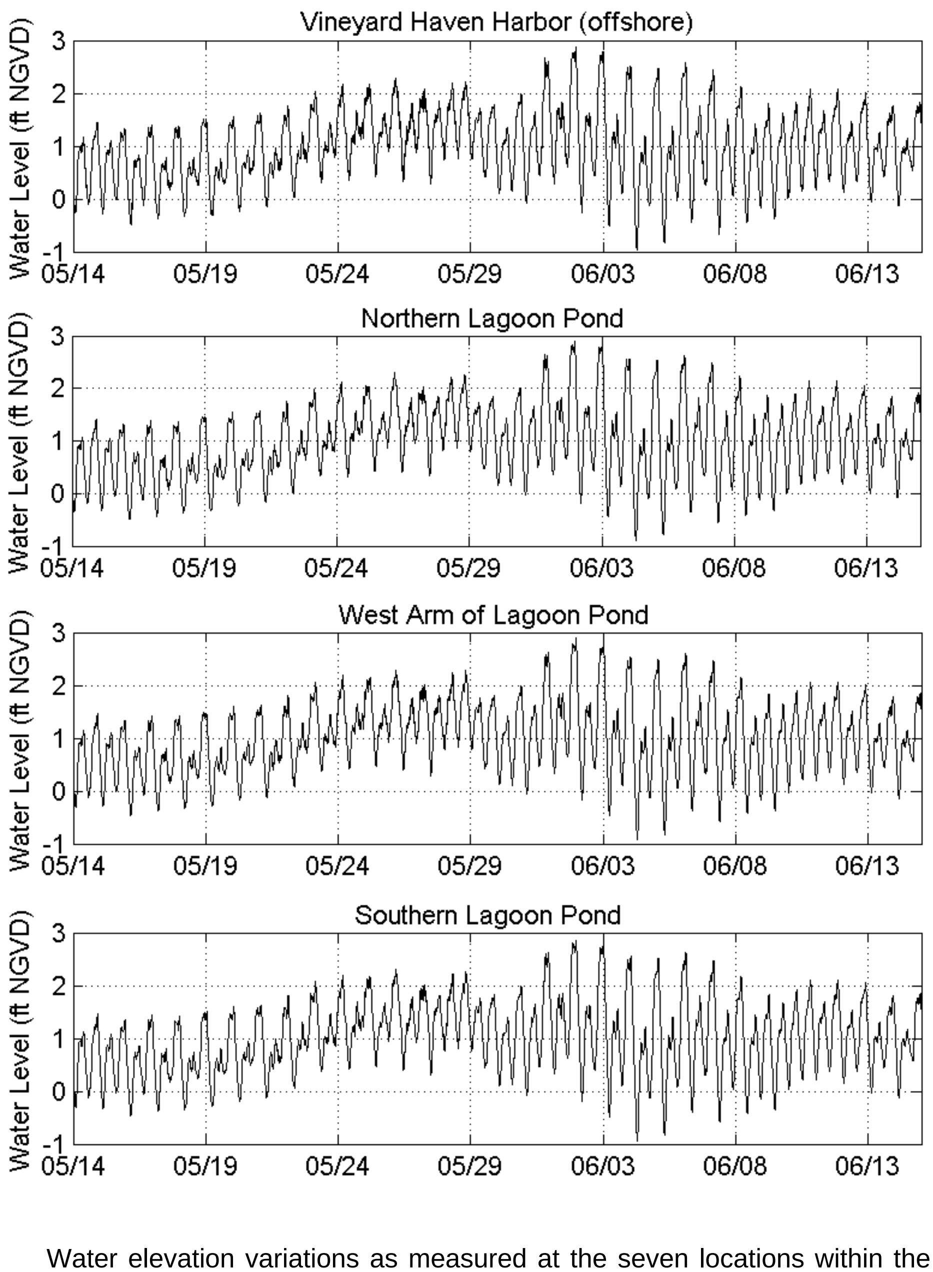


Figure V-4. Water elevation variations as measured at the seven locations within the Lagoon Pond system, between May 14 and June 15, 2004.

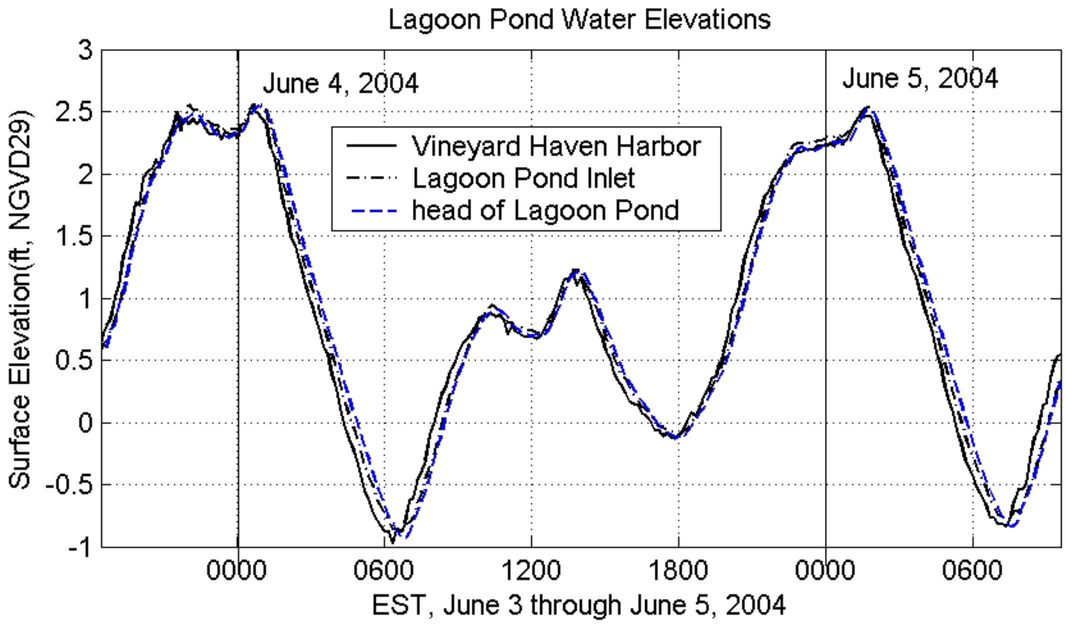


Figure V-5 Plot showing two tide cycles tides at three stations in the Lagoon Pond system plotted together. Demonstrated in this plot is the phase delay effect caused by the propagation of the tide through the estuary.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 32-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 Buzzards Bay 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 Lagoon Pond and Vineyard Haven Harbor compare well to similar datums computed for the south shore of Falmouth using a 38-day record from 1999 (MTL 0.8 ft, MHW 1.7 ft, MLW 0.0 ft NGVD).

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

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

Table V-2 presents the amplitudes of significant eight 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 0.65 feet in Vineyard Haven Harbor. The range of the M_2 tide is twice the amplitude, or about 1.30 feet. The diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar), possess amplitudes of approximately 0.34 and 0.28 feet respectively. The N_2 tide, a lunar constituent with a semi-diurnal period, is only slightly smaller than the main diurnal constituents with an amplitude of 0.24 feet. The M_4 tide, a higher frequency harmonic of the M_2 lunar tide (twice the frequency of the M_2), results from frictional dissipation of the M_2 tide in shallow water. Typically the M_4 represents a small fraction of the total tide amplitude. However, in Vineyard Sound, the M_4 and M_6 amplitudes are large compared to the M_2 (i.e., 25% and 9% of the M_2 amplitude, respectively), and as a result, they have more influence on the shape of the tide signal than is observed in most other corners of the world's oceans. The effect of the comparatively large amplitude of the M_4 and M_6 and their relative phases (+120 degrees for the M_4, and +15 degrees for the M_6, both relative to the M_2 phase) can be seen most clearly in Figure V-5 as the double peaks (due to the M_6) and flattened appearance (due to the M_4) of the high portions of the tide.

Table V-1. Tide datums computed from records collected in the Lagoon Pond system May 14 to June 15, 2004. Datum elevations are given relative to NGVD 29.

Tide Datum	Offshore (feet)	North Lagoon Pond (feet)	West Arm (South End Basin) (feet)	South Lagoon Pond (feet)
Maximum Tide	2.8	2.9	2.9	2.9
MHHW	2.0	2.0	2.0	2.0
MHW	1.7	1.7	1.7	1.7
MTL	0.9	0.9	0.9	0.9
MLW	0.0	0.0	0.1	0.1
MLLW	-0.2	-0.2	-0.2	-0.1
Minimum Tide	-1.1	-0.9	-0.9	-0.9

Table V-2. Tidal Constituents for stations in the Lagoon Pond System, from data collected May 14 through June 15, 2004.

	AMPLITUDE (feet)							
	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 Haven Harbor	0.65	0.16	0.06	0.06	0.24	0.34	0.28	0.15
Northern Lagoon Pond	0.66	0.15	0.06	0.06	0.25	0.34	0.28	0.17
Western Lobe of Lagoon Pond	0.65	0.15	0.06	0.06	0.24	0.33	0.27	0.16
Southern Lagoon Pond	0.65	0.15	0.06	0.06	0.25	0.34	0.28	0.17

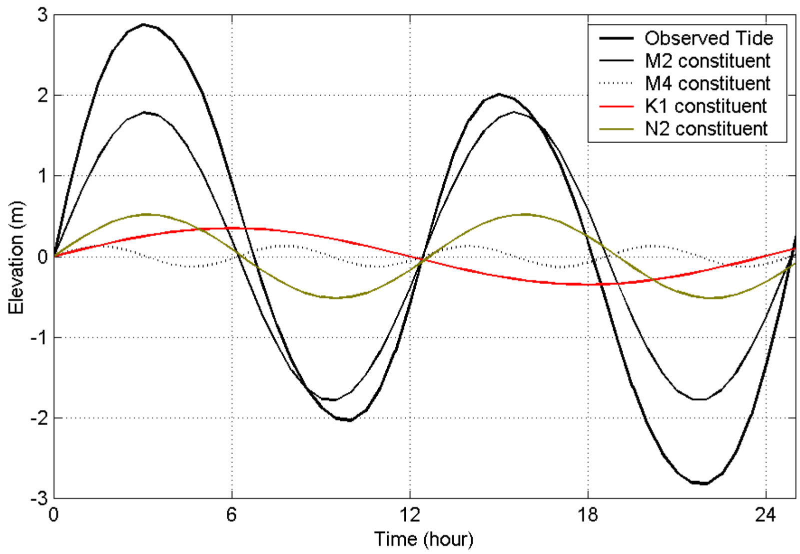


Figure V-6. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-3 presents the phase delay (in other words, the travel time required for the tidal wave to propagate throughout the system) of the M_2 tide at all tide gauge locations inside the Pond. The greatest delay occurs between the Vineyard Sound and Northern Lagoon Pond gauging stations. There is less phase delay of the tide inside the pond between the north and south ends, even though the distance between these stations is nearly three times farther. This suggests that there is some amount of tide attenuation caused by the inlet. However, the degree of attenuation is not significant relative to the hydraulic efficiency of the inlet because the effects of attenuation are observed only in the phase delay across the inlet, and not as a reduction in the amplitude of the tide.

Table V-3. M2 Tidal Attenuation, Lagoon Pond System, November-January 2004 (Delay in minutes relative to Vineyard Sound).

Location	Delay (minutes)
Northern Lagoon Pond	10.2
Western Lobe of Lagoon Pond	16.0
Southern Lagoon Pond	15.2

The tide data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. Non-tidal processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow. The results of an analysis to determine the energy distribution (or variance) of the original water elevation time series for the two river systems is presented in Table V-4 compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 23 constituents determined by the harmonic analysis). Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes are relative to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from Vineyard Sound, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual. Easily seen in the plot of Figure V-7, there is a steadily increasing residual tide during the period of time between May 14 and May 29. This exact same trend is observed in all four tide data records from the Pond and Vineyard Haven Harbor. Such a long period trend is likely due to shifts in the mean water elevation caused by regional scale influences such as Gulf Stream currents or seasonal weather patterns.

Table V-4 shows that the percentage contribution of tidal energy was essentially equal in all parts of the system, which indicates 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 81% of the water level changes in Lagoon Pond. The remaining 19% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of Vineyard and Nantucket Sounds. 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).

The results from Table V-4 indicate that hydrodynamic circulation throughout Lagoon Pond 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, for the hydrodynamic modeling effort described below, the actual tide signal from Vineyard Haven Harbor was used to force the model so that the effects of non-tidal energy are included in the modeling analysis.

Table V-4. Percentages of Tidal versus Non-Tidal energy, Lagoon Pond, November-January 2004

	Total Variance ($ft^2 \cdot sec$)	Tidal (%)	Non-tidal (%)
Vineyard Haven Harbor	0.45	81.2	18.8
Northern Lagoon Pond	0.47	80.4	19.6
Western Lobe of Lagoon Pond	0.45	80.5	19.5
Southern Lagoon Pond	0.45	81.1	18.9

V.2.3 ADCP Data Analysis

Cross-channel current measurements were surveyed through a complete tidal cycle at the Lagoon Pond inlet on May 24, 2004 to resolve spatial and temporal variations in tidal current patterns. The survey was designed to observe tidal flow across the inlet (as indicated in Figure V-2) at half-hourly intervals. The data collected during this survey provided information that was necessary to model properly the hydrodynamics of the two riverine estuary systems. Figures V-8 and V-9 show color contours of the current measurements observed during the flood and ebb tides at each of the three transects. Positive along-channel currents (top panel)

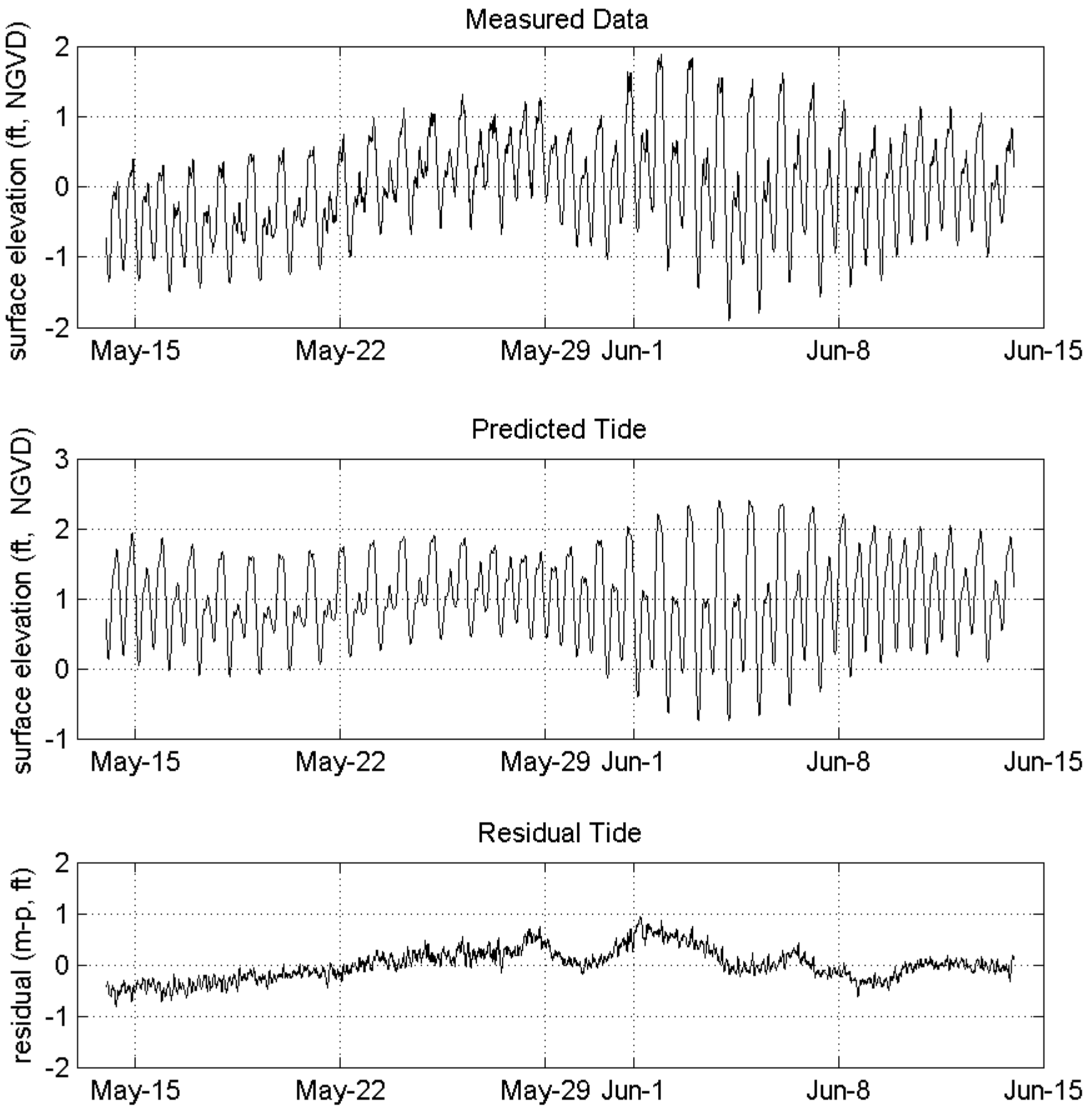


Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured in Vineyard Haven Harbor (TG-1).

indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Therefore, for this survey, positive along-channel flow is to the southeast, and positive cross-channel flow is moving to the southwest. In Figures V-8 and V-9, the lower left panel shows depth-averaged currents across the channel projected onto a 1999 aerial photograph of the transect vicinity. The lower right panel of each figure indicates the stage of the tide that the survey transect was taken by the vertical line plotted with the tide elevation curve.

Maximum measured currents in the water column were 2.5 ft/sec during the flood portion of the tide and 1.7 ft/sec during the ebb at the inlet. Maximum measured flood flows during flooding portions of the tide were 3150 ft^3/sec into the Pond. During ebbing portions of the tide, the maximum discharge flow from the Pond were 2700 ft^3/sec.

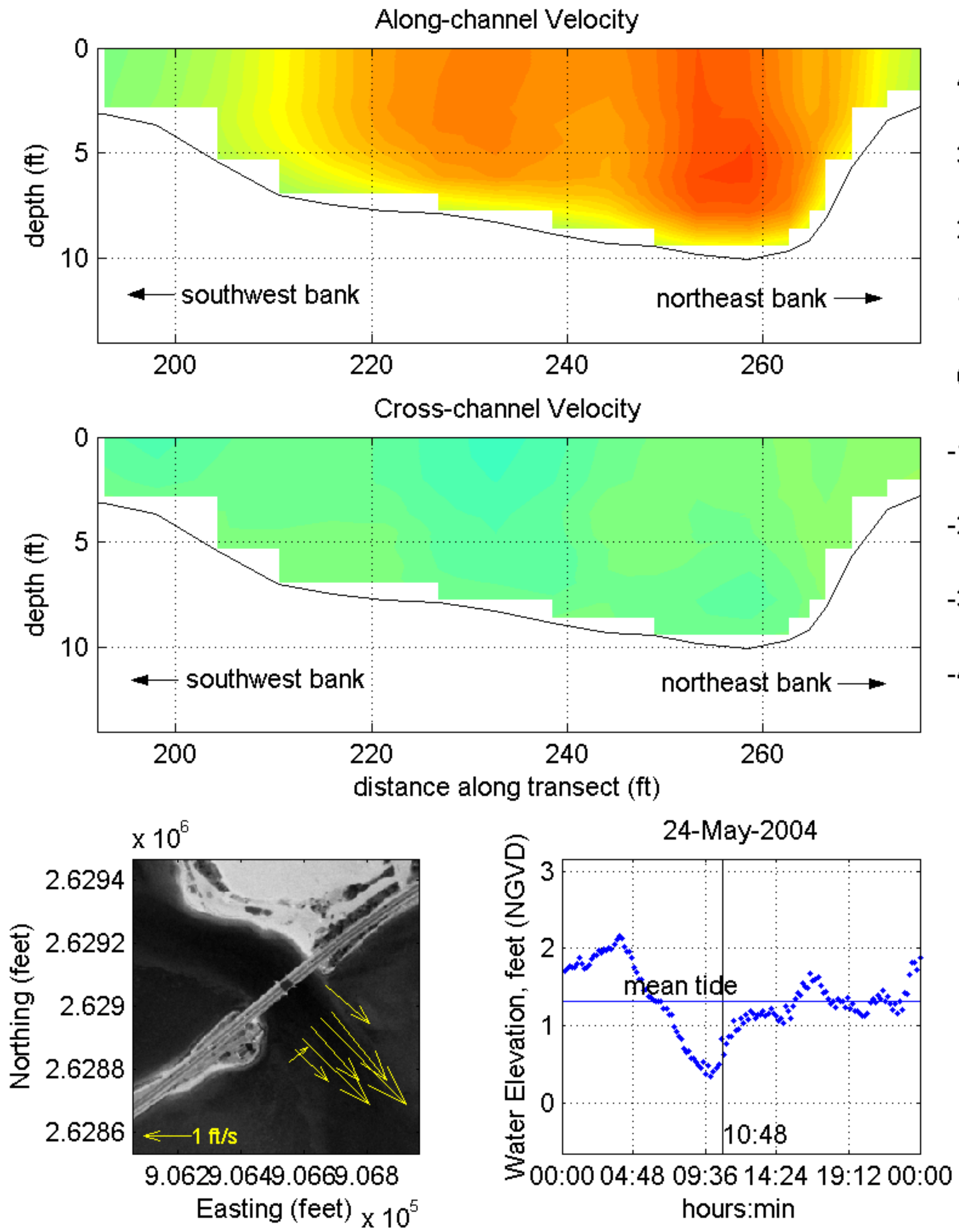


Figure V-8. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across Lagoon Pond inlet, measured at 10:48 EST on May 24, 2004 during the period of maximum flood tide currents. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Lower left plot shows scaled velocity vectors projected onto a 1999 aerial photo of the survey area. A tide plot for the survey day is also given.

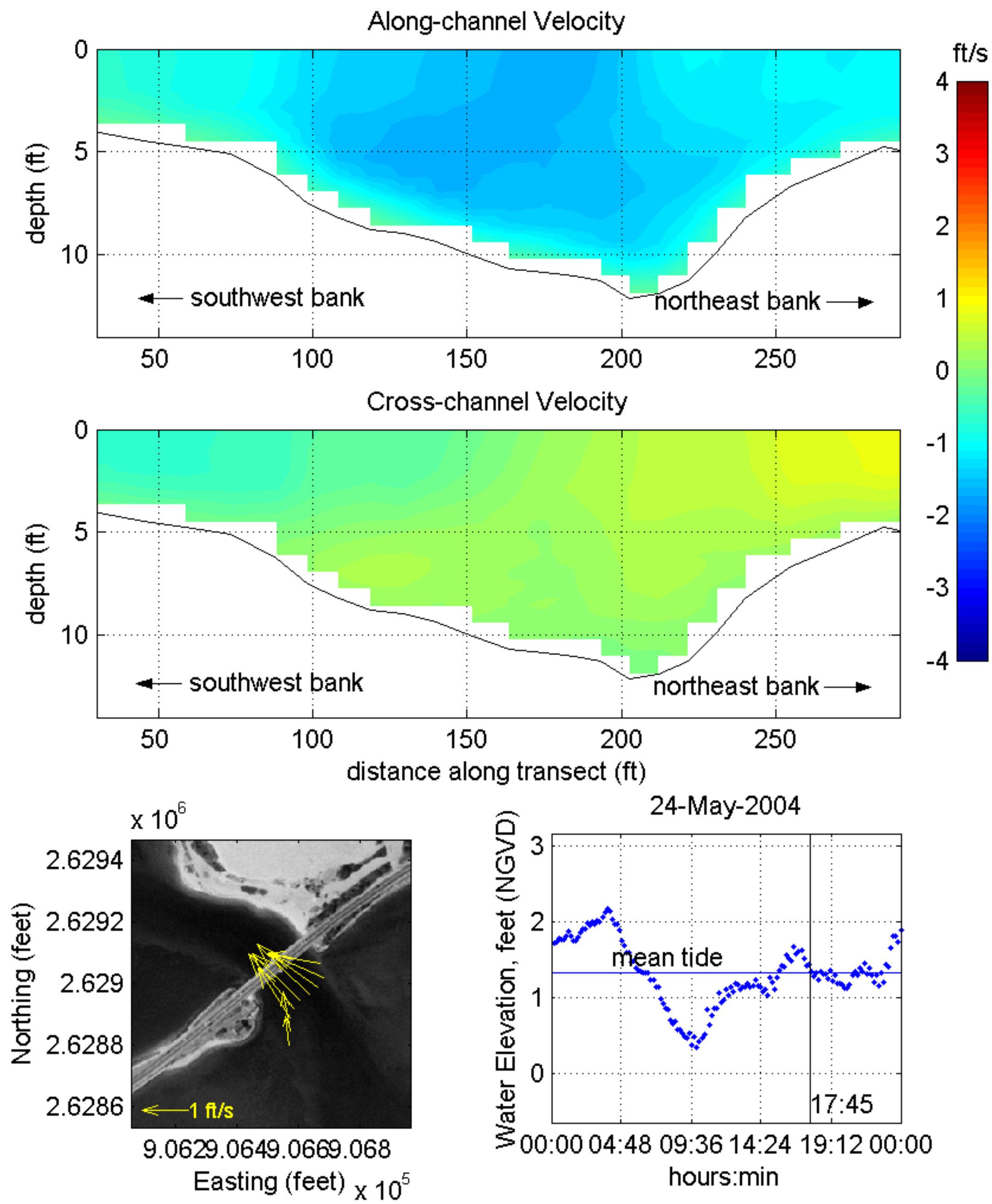


Figure V-9. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across Lagoon Pond inlet, measured at 17:45 EDT on May 24, 2004 during the period of maximum ebb tide currents. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Lower left plot shows scaled velocity vectors projected onto a 1999 aerial photo of the survey area. A tide plot for the survey day is also given.

V.3 HYDRODYNAMIC MODELING

The focus of this study was the development of a numerical model capable of accurately simulating hydrodynamic circulation within the Lagoon Pond estuary system. Once calibrated, the model was used to calculate water volumes for selected sub-embayments [e.g., the West Arm (South End Basin) and the upper estuarine reach of Lagoon Pond] 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 Lagoon Pond 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 of estuary systems in southeast Massachusetts, including systems in Chatham, Falmouth’s ‘finger’ ponds, and Popponesset Bay.

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 Surface water 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-2V:

- 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 Have Harbor. 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 (15+) model calibration simulations for each system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid Generation

The grid generation process for the model was assisted through the use of the SMS package. The digital shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary with 2163 elements and 5547 nodes (Figure V-10). All regions in the system were represented by two-dimensional (depth-averaged) elements. The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties within the estuary. Fine resolution was required to simulate the numerous channel constrictions (e.g., at the bridge crossings over the two Rivers) 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-11. 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.

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 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 Lagoon Pond.

The model was forced at the open boundary using water elevations measurements obtained in Vineyard Haven Harbor (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 Haven Harbor 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 Harbor).

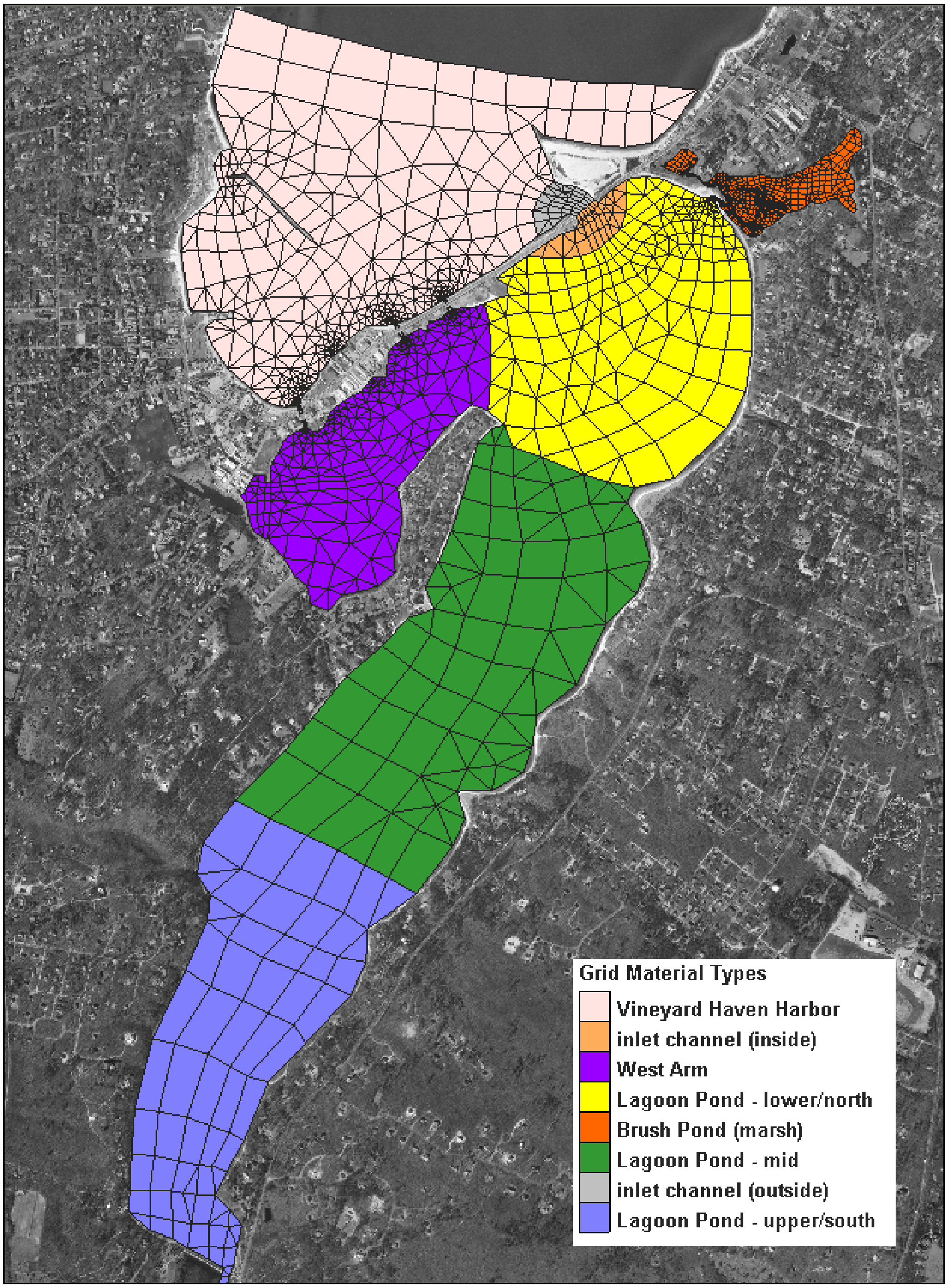


Figure V-10. The model finite element mesh developed for Lagoon Pond estuary system. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained in Nantucket Sound.

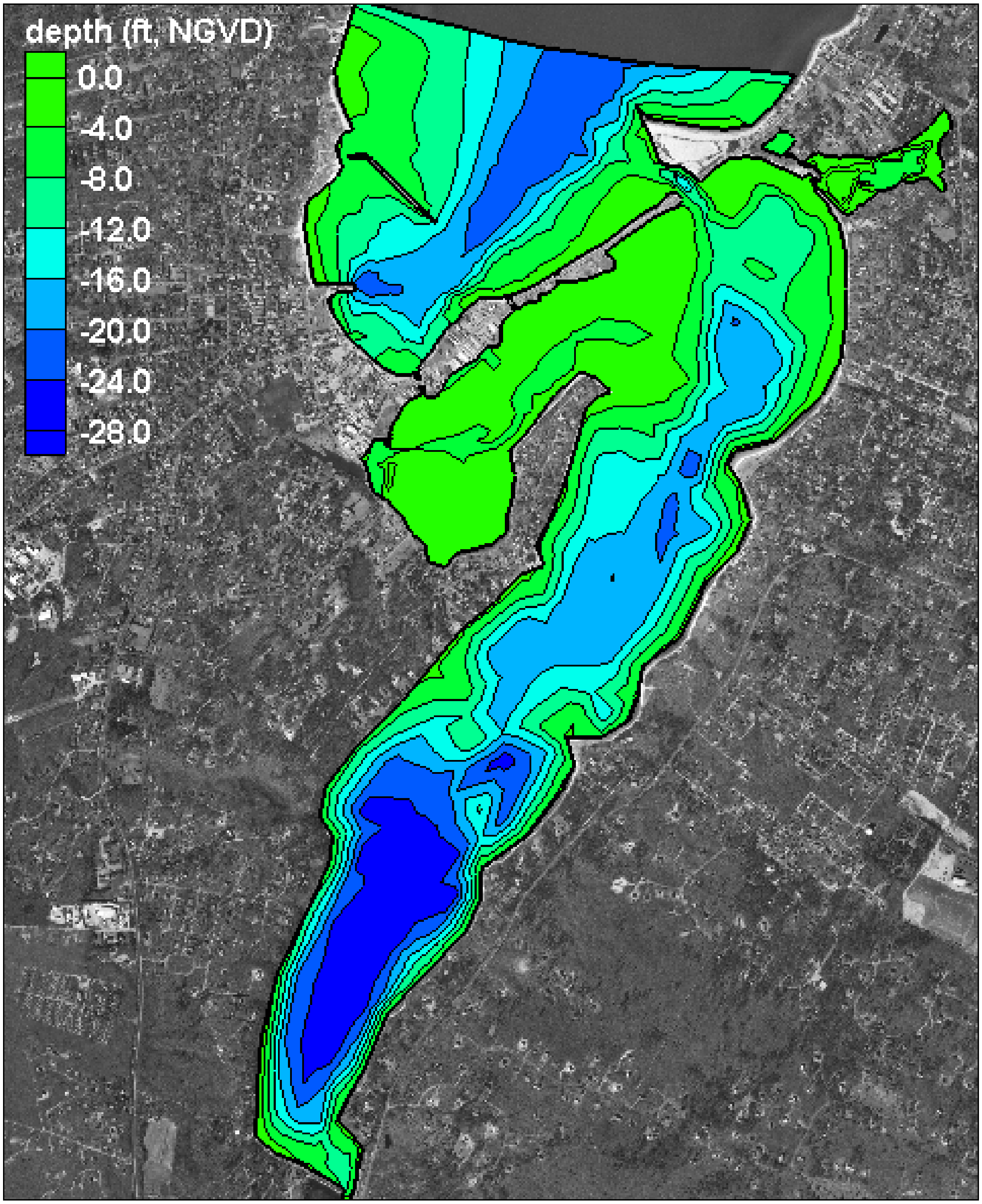


Figure V-11. Depth contours of the completed Lagoon Pond finite element mesh.

V.3.3 Calibration

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

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

The calibration was performed for an approximate eight-day period, beginning 1700 hours EDT May 24, 2004 and ending 11:12 EDT June 1, 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 7.75 day period, the tide ranged approximately 2.7 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 Brush Pond, damping of flow velocities typically is controlled more by “form drag” associated with marsh plants than the bottom friction described above. However, simulation of this “form drag” is performed using Manning’s coefficients as well, with values ranging from 2-to-10 times friction coefficients used in sandy channels. Final calibrated friction coefficients (listed in Table V-5) were largest for marsh plain area, where values were set at 0.07. 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
Vineyard Haven Harbor	0.025
Inlet Channel (inside)	0.025
West Arm (South End Basin) of Lagoon Pond	0.025
Lagoon Pond – lower/north	0.025
Brush Pond (marsh)	0.070
Lagoon Pond - mid	0.025
Inlet channel (outside)	0.025
Lagoon Pond – upper/south	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$^{2)}$
Vineyard Haven Harbor	80
Inlet Channel (inside)	80
West Arm (South End Basin) of Lagoon Pond	80
Lagoon Pond – lower/north	80
Brush Pond (marsh)	200
Lagoon Pond - mid	80
Inlet channel (outside)	80
Lagoon Pond – upper/south	80
Vineyard Haven Harbor	80

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

V.3.3.4 Comparison of Modeled Tides and Measured Tide Data

Several calibration model runs were performed to determine how changes to various parameters (e.g. friction and turbulent exchange coefficients) affected the model results. These trial runs achieved excellent agreement between the model simulations and the field data. Comparison plots of modeled versus measured water levels at the seven gauge locations is presented in Figures V-12 through V-15. 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 0.01 inch for all locations, suggesting the model accurately predicts tidal hydrodynamics within Lagoon Pond. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the calibration time period are shown in Table V-7. The constituent values in for the calibration time period differ from those in Tables V-2 because constituents were computed for only 7.75 days, rather than the entire 32-day period represented in Tables V-2. Errors associated with tidal constituent height were on the order of hundredths of feet, which was an order of magnitude better than the accuracy of the tide gage gauges (±0.12 ft). Time lag errors were less than the time increment resolved by the model and measured tide data (1/6 hours or 10 minutes), indicating good agreement between the model and data.

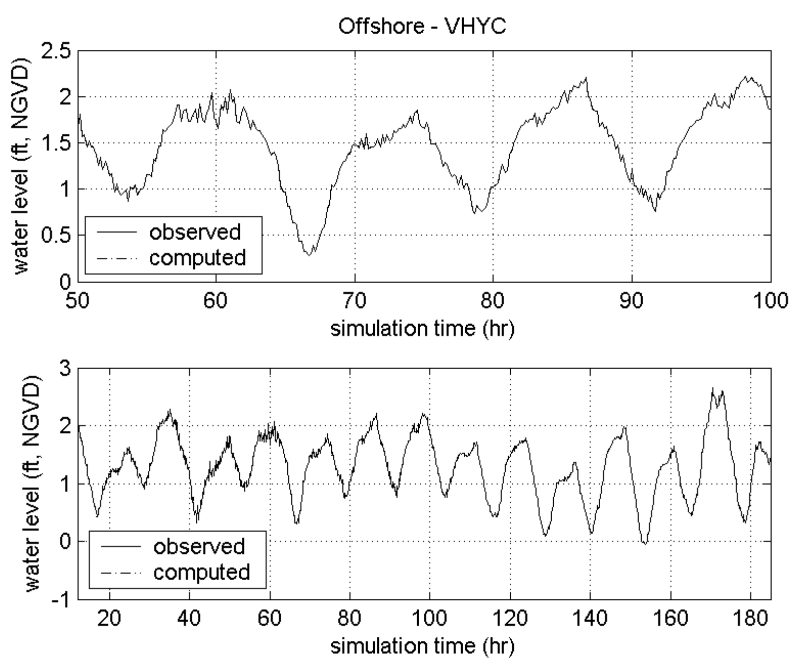


Figure V-12. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the calibration time period, for the offshore gauging station. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

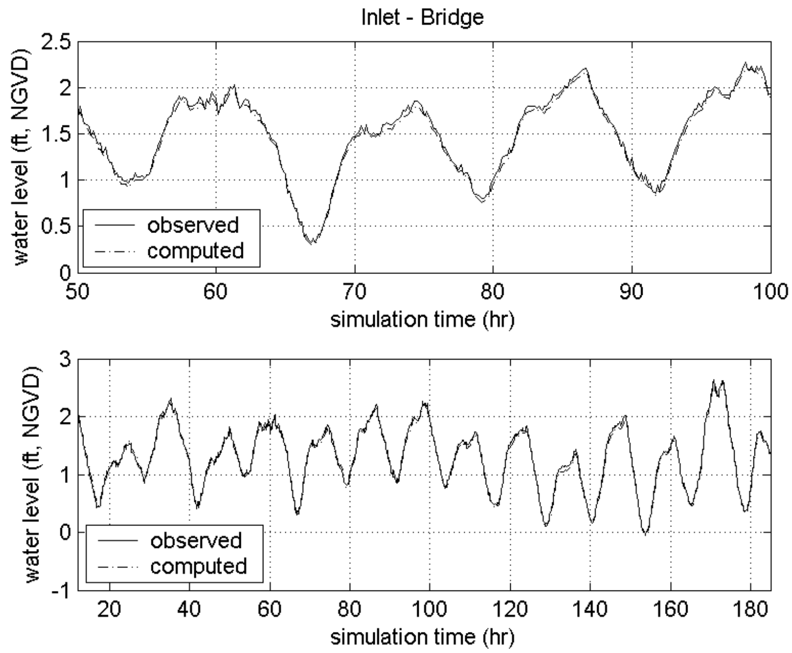


Figure V-13. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Lagoon Pond inlet gauging station (WR-2). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

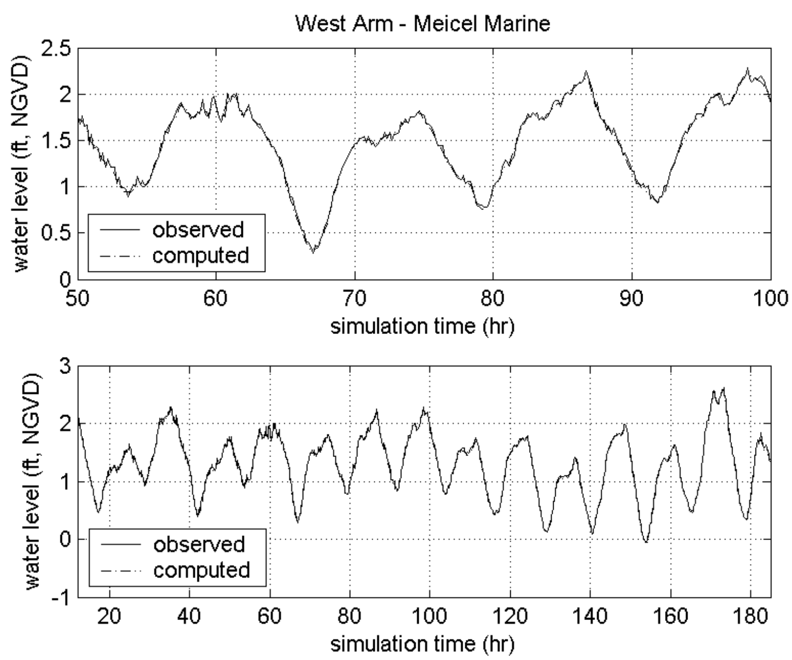


Figure V-14. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the West Arm (South End Basin) gauging station (WR-3). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

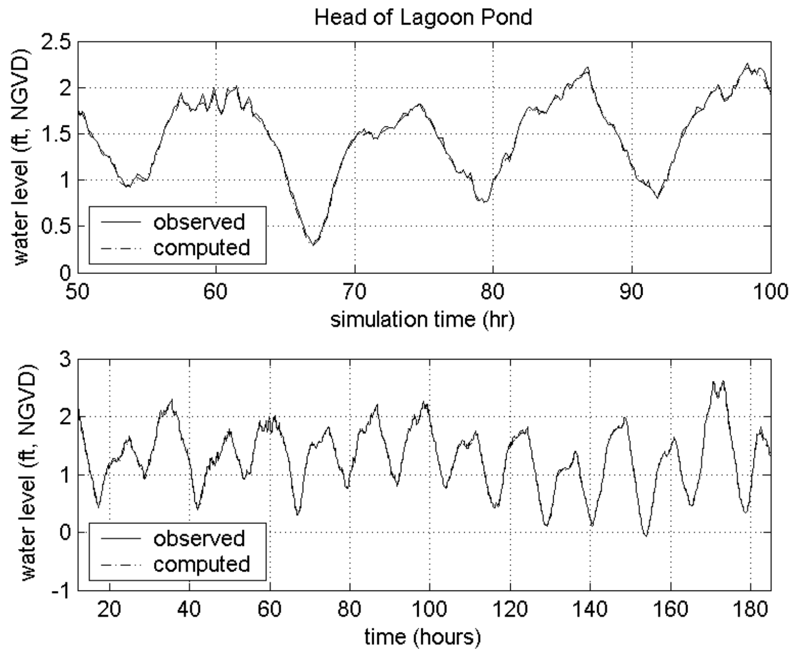


Figure V-15. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the gauging station at head of Lagoon Pond (WR-4). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

Table V-7. Comparison of Tidal Constituents calibrated RMA2 model versus measured tidal data for the period May 24 to June 1, 2003.

Model Verification Run						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Offshore - VHYC	0.59	0.16	0.05	0.19	-36.1	84.8
Lagoon Pond Inlet	0.59	0.15	0.05	0.19	-31.0	95.9
West Arm (South End Basin)	0.59	0.15	0.05	0.19	-30.1	97.5
Lagoon Pond Head	0.59	0.16	0.05	0.19	-30.2	97.4
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Offshore - VHYC	0.59	0.16	0.05	0.18	-36.7	84.1
Lagoon Pond Inlet	0.60	0.15	0.05	0.19	-32.8	94.1
West Arm (South End Basin)	0.59	0.16	0.06	0.18	-30.6	97.5
Lagoon Pond Head	0.59	0.16	0.06	0.18	-30.9	96.7
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Offshore - VHYC	0.00	0.00	0.00	0.01	1.0	0.6
Lagoon Pond Inlet	-0.01	0.00	0.00	0.00	3.0	1.6
West Arm (South End Basin)	0.00	0.00	0.00	0.01	0.9	0.0
Lagoon Pond Head	0.01	0.00	0.00	0.00	1.3	0.5

V.3.4 ADCP verification of the Lagoon Pond system

An additional model verification check was possible by using collected ADCP velocity data to verify the performance of the two arm (east arm and west arm) system included in the model. 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 Lagoon Pond model was run for the period covered during the ADCP survey on May 24, 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 Pond inlet

Data comparisons at the river mouth ADCP transects show good agreement with the model predictions, with R^2 correlation coefficients between data and model results are 0.91 and an RMS error that is 9% of the maximum flow through the inlet. A comparison of the measured and modeled volume flow rates at the survey transect are shown in Figure V-16. 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 (blue 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.

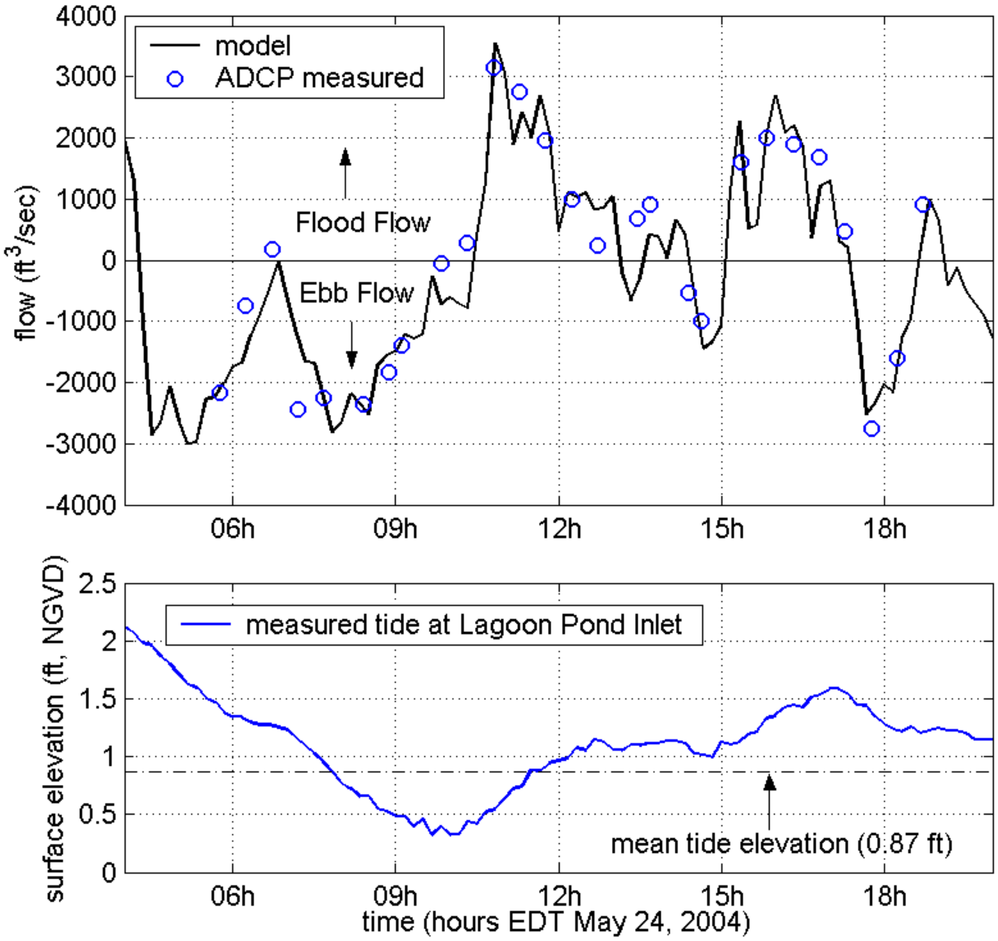


Figure V-16. Comparison of measured volume flow rates versus modeled flow rates (top plot) across Lagoon Pond inlet, over a tidal cycle on May 24, 2004 (R^2 = 0.91). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation at the Lagoon Pond inlet in Vineyard Haven Harbor.

V.4.2.3.5 Model Circulation Characteristics

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

From the model run of the two arm (east arm and west arm) estuary system, maximum flood velocities at the inlet are slightly larger than velocities during the ebb portion of the tide. Maximum depth-averaged velocities in the model are approximately 2.9 feet/sec for flooding tides, and 2.2 ft/sec for ebbing tides. A close-up of the model output is presented in Figure V-17, which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow, for a single model time-step, at the portion of the tide where maximum flood velocities occur at the inlet.

In addition to depth averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs through the Pond inlet is seen in Figure V-18. During the simulation time period, maximum modeled flood tide flow rates through the inlet were 5,600 ft^3/sec. Maximum ebb tide flow rates for this same period were 4,800 ft^3/sec.

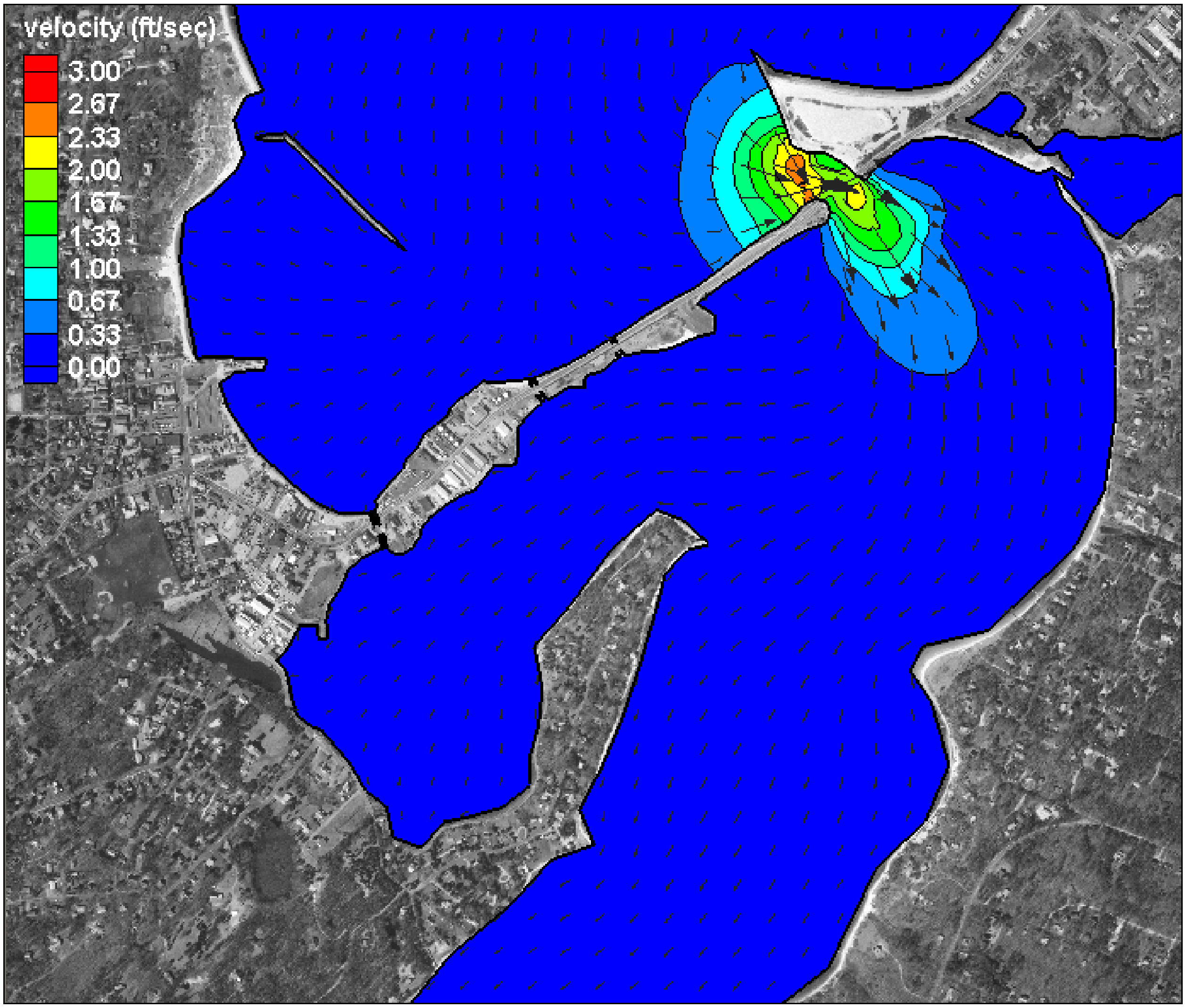


Figure V-17. Example of hydrodynamic model output in Lower Lagoon Pond for a single time step where maximum flood velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

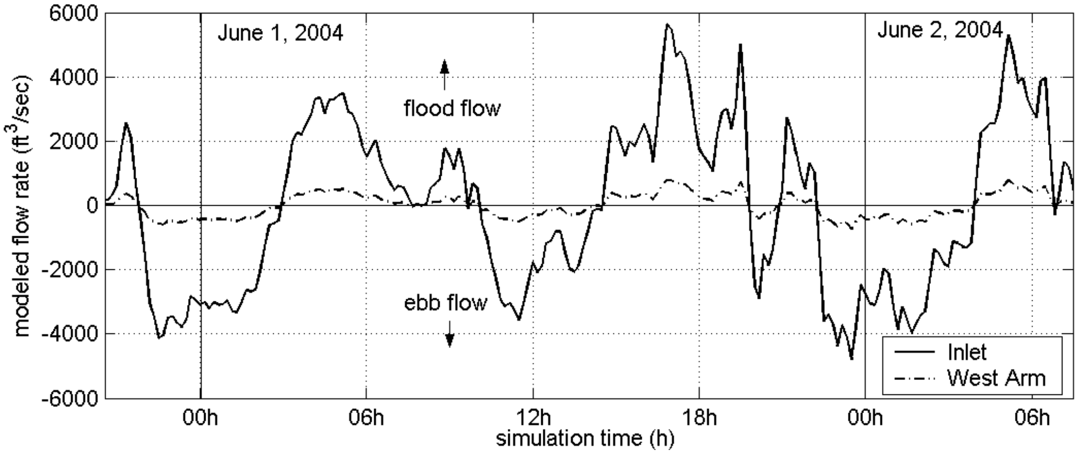


Figure V-18. Time variation of computed flow rates for transects across Lagoon Pond inlet and the entrance to the West Arm (South End Basin) of Lagoon Pond. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are likewise large compared to neap tide conditions. Positive flow indicates flooding tide, while negative flow indicates ebbing tide.

V.5 FLUSHING CHARACTERISTICS

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

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

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

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

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using the head of Lagoon Pond as an example, the **system residence time** is the average time required for water to migrate from the head of Lagoon Pond, through the lower portions of the Pond, and finally into Vineyard Haven Harbor, where 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 the Lagoon Pond and its component sub-embayments.

The volume of the each sub-embayment, as well as their respective tidal prisms, were computed as cubic feet (Table V-8). Model divisions used to define the system sub-embayments for the two systems include 1) the whole of Lagoon Pond, 2) the West Arm (South End Basin) of Lagoon Pond, 3) the head of Lagoon Pond (upper one-third of the main basin), 4) mid Lagoon Pond (the upper two-thirds of the Pond) , and 5) Brush Pond. The model computed total volume of each sub-embayment (using the divisions shown in Figure V-10), at every time step, and this output was used to calculate mean sub-embayment volume and average tide prism. Since the 7.75-day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

Residence times were averaged for the tidal cycles comprising a representative 7.75 day period (15 tide cycles), and are listed in Table V-9. Residence times were computed for the entire estuary, as well selected sub-embayments within the two systems. In addition, **system** and **local residence times** were computed to indicate the range of conditions possible for the system. Residence times were calculated as the volume of water (based on mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days.

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

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Lagoon Pond	304,279,000	33,555,000
West Arm (South End Basin)	14,132,000	4,757,000
Lagoon Pond – head	117,370,000	8,376,000
Lagoon Pond - mid	235,019,000	19,839,000
Brush Pond	1,765,000	457,000

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

Embayment	Local Residence Time (days)	System Residence Time (days)
Lagoon Pond	4.7	4.7
West Arm (South End Basin)	1.5	33.1
Lagoon Pond – head	7.3	18.8
Lagoon Pond - mid	6.1	7.9
Brush Pond	2.0	344.6

The moderately high local residence time (4.7 days) of the whole Lagoon Pond system shows that it has less than ideal flushing conditions, and therefore, water quality within the system is highly sensitive to the combined nutrient load input from the system watersheds, benthic sediments and direct atmospheric deposition. The less-than-ideal flushing ability of the Pond is not due to an undersized inlet, but rather the muted tide range in Vineyard Sound. Compared to other estuary systems with better tidal exchange, Lagoon Pond would likely show signs of eutrophy with a lower rate of nutrient loading.

In some areas of Lagoon Pond local flushing rates are better than the average for the entire system. The West Arm (South End Basin) and Brush Pond have residence times that are less than or equal to 2.0 days. Computed residence times for these two sub-embayments are lower because their mean volumes are smaller relative to their tide prism, especially in the case of Brush Pond which includes areas of marsh plain. Due to their low flushing rates, water quality in these areas of Lagoon Pond is strongly dependent upon the health of the remainder of the estuary. If water quality conditions are good in the main basin of the Pond, then the West Arm (South End Basin) and Brush Pond would likely have good conditions as well. Alternately, if water quality measurements indicate poor estuarine health in these areas, it would be likely a result of poor conditions in the main basin of the Pond.

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 Lagoon Pond 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 and Vineyard Haven Harbor typically is strong because of the effects of the local winds, tidal induced mixing, the “strong littoral drift” assumption should cause only minor errors in residence time calculations.

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

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

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the embayments were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated hydrodynamic model representing the transport of water within the Lagoon Pond system. Files of node locations and node connectivity for the RMA-2V model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic model output used for the water quality model calibration was the 14.5 day (28 tide cycle) period beginning November 9, 2004 2245 EST. This period overlaps with that used in the flushing analysis presented in Chapter V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic “steady state”, and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

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

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. The multi-year averages present the “best” comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. Seven years of data (collected between 2002 and 2008) were available at most stations.

Table VI-1. Measured data and modeled Nitrogen concentrations for the Lagoon Pond estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data represented in this table were collected in the summers of 2002 through 2007.

Sub-Embayment	MEP monitoring station	data mean	s.d. all data	N	model min	model max	model average
Lagoon Pond head at dike	LGP-6	0.418	0.071	23	0.408	0.424	0.413
Lagoon Pond Head	LGP-4	0.384	0.077	100	0.384	0.387	0.385
Lagoon Pond upper Basin	LGP-2	0.360	0.067	135	0.370	0.372	0.371
Lagoon Pond mid Basin	LGP-8	0.359	0.070	66	0.334	0.342	0.338
Lagoon Pond lower Basin	LGP-9	0.333	0.058	60	0.322	0.336	0.328
West Arm (South End Basin)	LGP-10	0.386	0.075	35	0.370	0.391	0.378
Nantucket Sound	NTKS	0.290	0.052	48	-	-	-

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

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

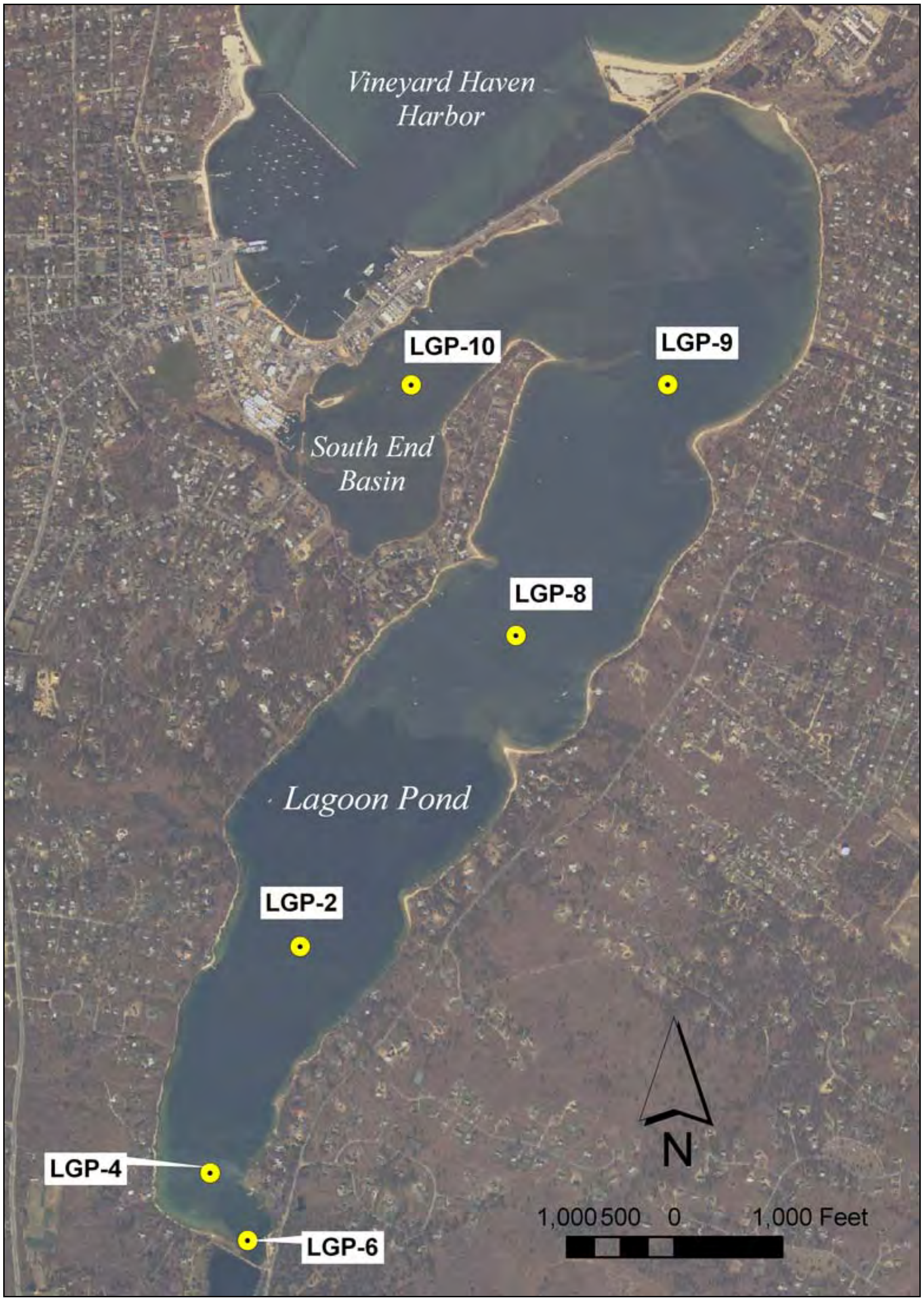


Figure VI-1. Estuarine water quality monitoring station locations in the Lagoon Pond estuary system. Station labels correspond to those provided in Table VI-1.

VI.2.1 Model Formulation

The formulation of the model is for two-dimensional depth-averaged systems in which concentration in the vertical direction is assumed uniform. The depth-averaged assumption is justified since vertical mixing by wind and tidal processes prevent significant stratification in the modeled sub-embayments. To confirm the assumption a review of salinity and temperature data obtained from the water quality monitoring program and collected through the summer months of 2004 through 2007 (four separate summers) was completed. These data show that stratification in the deep basin of the upper pond does not occur. Salinity and temperature data are available from surface, middle and bottom samples at station LGP 2. The middle sample is taken from a depth of 13.1 feet (4.0 meters) below the surface, while the bottom sample is from 24.6 feet (7.5 meters) below the surface. From the SMAST data record, the mean salinity difference between the surface and bottom samples is 0.5 ppt, with a standard deviation of 0.7 ppt. The mean surface sample salinity is 30.5 ppt, while the mean bottom sample salinity is 31.0 ppt. The mean temperature difference between surface and bottom samples is -1.6 degrees C, with a standard deviation of 1.0 degrees C. The small differences between surface and bottom measurements, for both temperature and salinity, indicate that there are no periods of significant stratification of the pond during the summer months. 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; Dx and Dy are the model dispersion coefficients in the x and y directions; and σ is the constituent source/sink term. Since the model utilizes input from the RMA-2 model, a similar implicit solution technique is employed for the RMA-4 model.

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

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

VI.2.2 Water Quality Model Setup

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

For each model, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 14.5 tidal-day (348 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the Lagoon Pond model.

VI.2.3 Boundary Condition Specification

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

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

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in Vineyard Haven Harbor was set at 0.290 mg/L, based on SMAST data.

Table VI-2. Sub-embayment and surface water loads used for total nitrogen modeling of the Lagoon Pond 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)
Lagoon Pond	36.208	7.156	36.756
West Arm (South End Basin)	5.762	0.921	10.105
Upper Lagoon Pond Stream	4.827	-	-
System Total	46.797	8.077	46.862

VI.2.4 Model Calibration

Calibration of the total nitrogen model of Lagoon Pond proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data.

Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (*E*) values were varied through the modeled system by setting different values of *E* for each grid material type, as designated in Section V. Observed values of *E* in 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 mid-point between maximum modeled TN and average modeled TN was compared to mean measured TN data values, at each water-quality monitoring station. The calibration target would fall near the modeled mean because the monitoring data are collected, as a rule, during mid ebb tide.

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

Embayment Division	E m^2/sec
Vineyard Haven Harbor	50.0
Inlet Channel	50.0
West Arm (South End Basin) of Lagoon Pond	4.0
Brush Pond (marsh)	5.0
Lagoon Pond – lower/north	50.0
Lagoon Pond - mid	30.0
Lagoon Pond – upper/south	6.5

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for each system. Computed root mean squared (rms) error is 0.01 mg/L and the calculated R^2 correlation is 0.85, both of which demonstrate an excellent fit between modeled and measured data for this system.

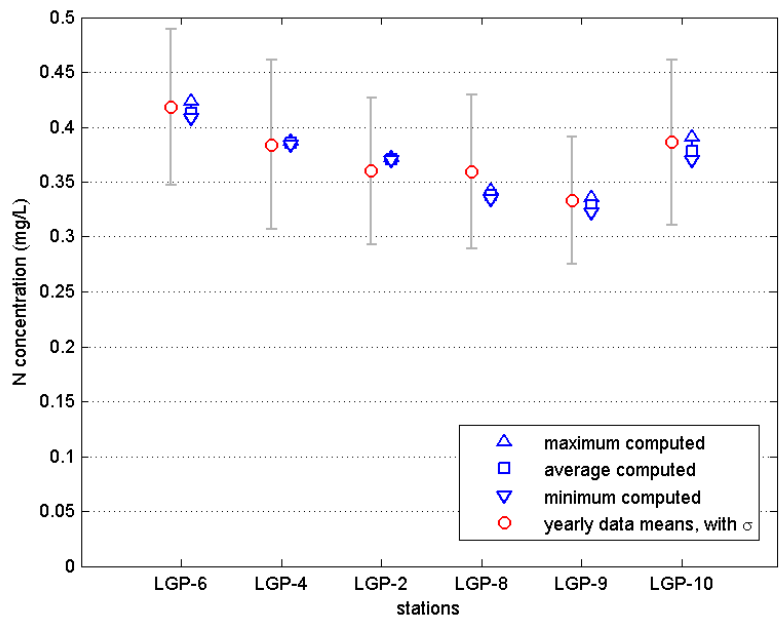


Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Lagoon Pond system. Station labels correspond with the MEP IDs provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation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

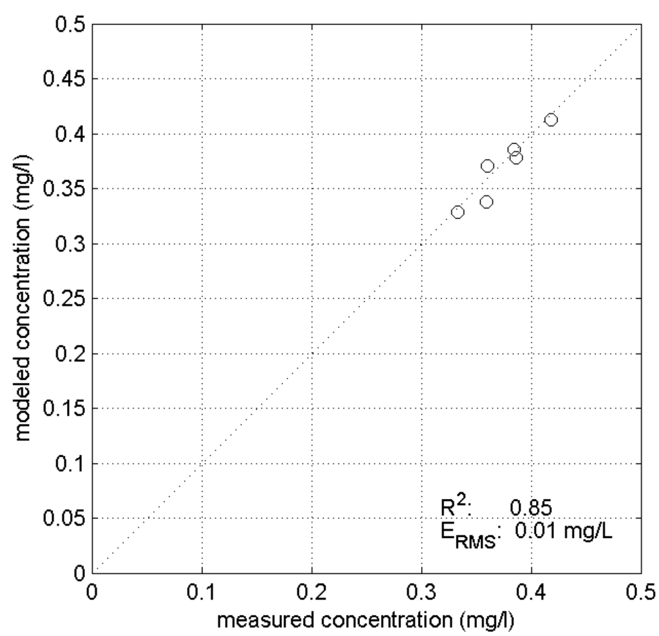


Figure VI-3. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are 0.85 and 0.01 mg/L respectively.

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

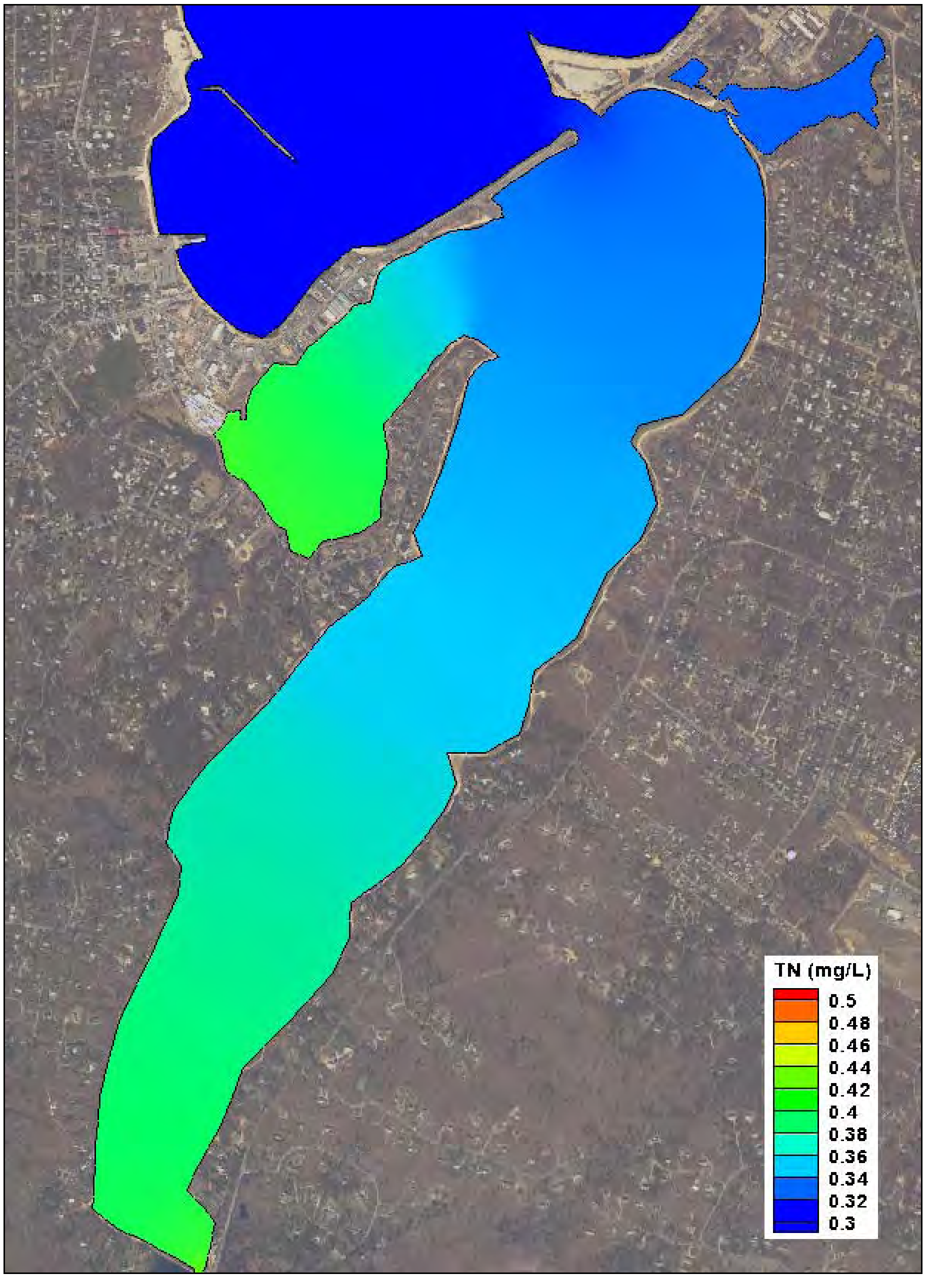


Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Lagoon Pond system.

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 Lagoon Pond system using salinity data collected at the same stations as the nitrogen data. Comparisons of modeled and measured salinities are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. The RMS error and R^2 correlation for the salinity verification are 0.5 ppt and 0.80 respectively. Again, these model statistics indicate the excellent quality of the fit between the measured data and model output, and therefore the great skill of the model to simulate the physical system.

The only required inputs into the RMA4 salinity model of the system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, and groundwater inputs. The open boundary salinity was set at 31.8 ppt. Surface water and groundwater input salinities were set at 0 ppt. The stream input at the head of the Pond was set to 2.6 ft^3/sec (6,516 m^3/day). Combined groundwater and direct precipitation inputs used for the model were 11.2 ft^3/sec (23,393 m^3/day) for the main Lagoon Pond watershed and 0.9 ft^3/sec (1620 m^3/day) for the West Arm (South End Basin). Groundwater and precipitation flows were distributed evenly in the model through the use of several elements positioned along the model's land boundary. Dispersion coefficients used in the salinity model were exactly the same as those used in the TN model.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

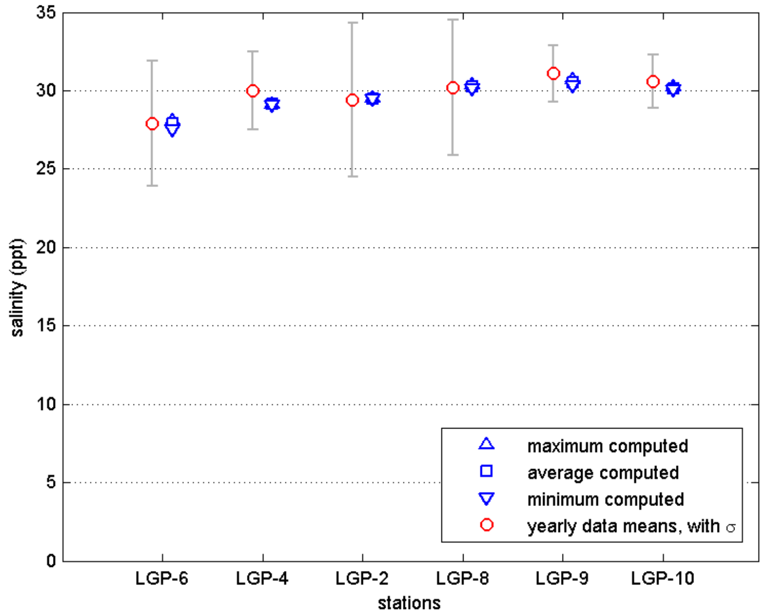


Figure VI-5. Comparison of measured and calibrated salinity model output at stations in Lagoon Pond. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along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

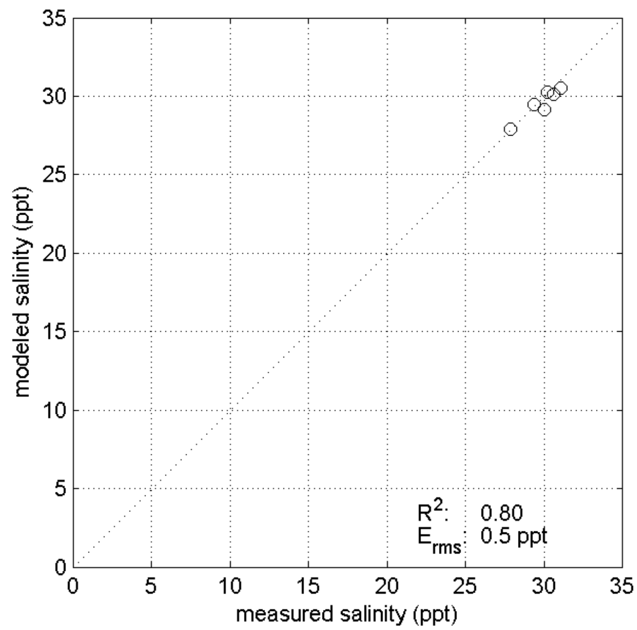


Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. Computed RMS error for this model verification run is 0.5 ppt.

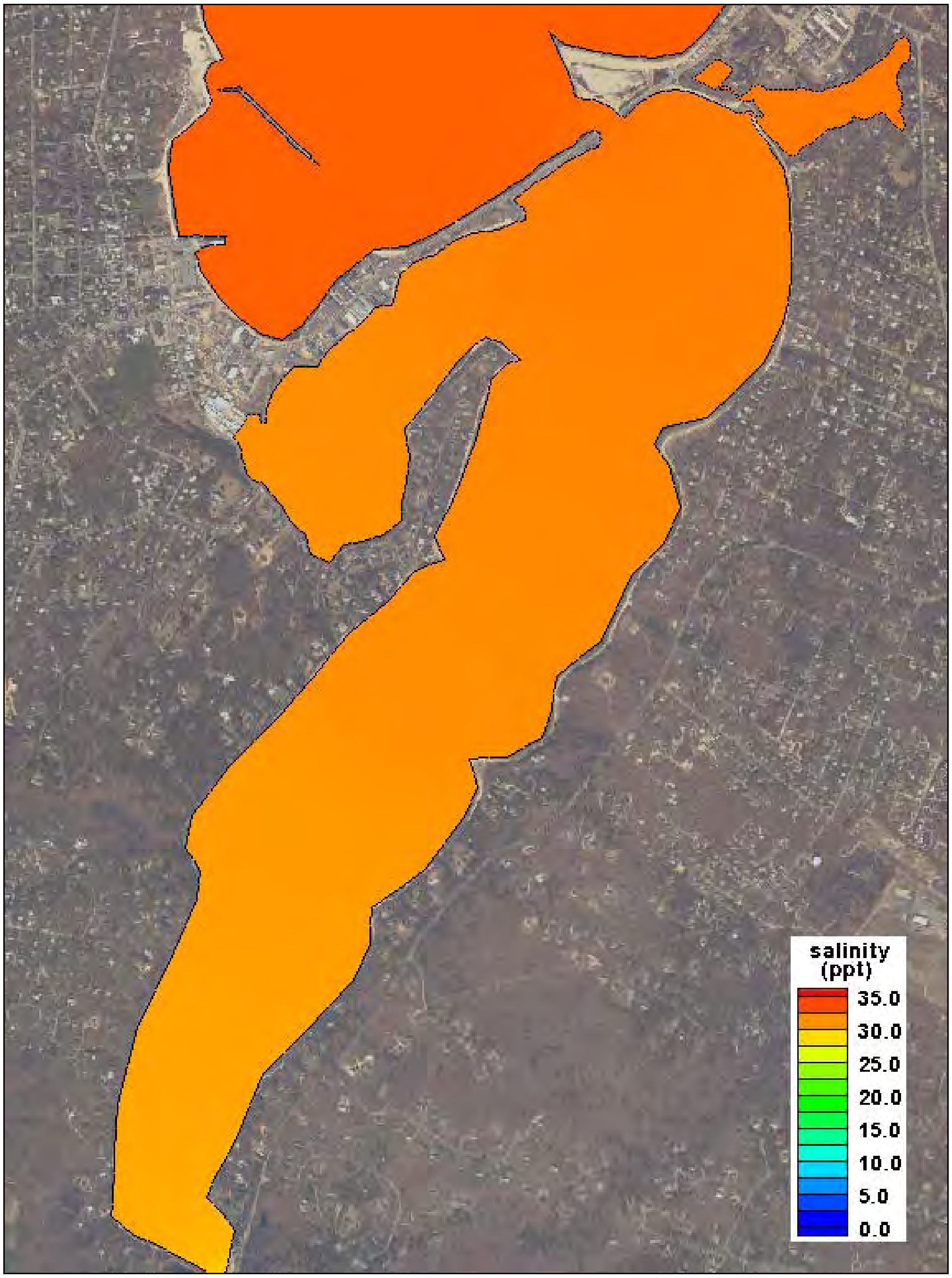


Figure VI-7. Contour Plot of average modeled salinity (ppt) in the Lagoon Pond system.

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

sub-embayment	present load (kg/day)	build-out (kg/day)	build-out % change	no load (kg/day)	no load % change
Lagoon Pond	36.208	52.808	+45.8%	0.827	-95.0%
West Arm (South End Basin)	5.762	7.970	+38.3%	0.164	-97.1%
Upper Lagoon Pond Stream	4.827	5.145	+6.6%	0.529	-89.0%
System Total	46.797	65.923	+40.9%	2.521	-94.6%

VI.2.6.1 Build-Out

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

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Lagoon Pond	52.808	7.156	39.670
West Arm (South End Basin)	7.970	0.921	11.980
Upper Lagoon Pond Stream	5.145	-	-
System Total	65.923	8.077	51.650

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of the system was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Vineyard Haven Harbor) remained identical to the existing conditions modeling scenarios. For build-out, the increase in modeled TN concentrations is greatest in the West Arm (South End Basin), where TN concentrations increase more than 20% at all monitoring stations. The percent change P over background presented in Table VI-6 is calculated as:

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

where N is the nitrogen concentration at the indicated monitoring station for present and threshold conditions, and also in Nantucket Sound (background). A contour plot showing average TN concentrations throughout the Pond system is presented in Figure VI-8 for the model of build-out loading.

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 Haven Harbor (0.290 mg/L), for the Lagoon Pond system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out (mg/L)	% change
Lagoon Pond head at dike	LGP-6	0.413	0.438	+20.0%
Lagoon Pond Head	LGP-4	0.385	0.407	+23.1%
Lagoon Pond upper Basin	LGP-2	0.371	0.390	+24.4%
Lagoon Pond mid Basin	LGP-8	0.338	0.351	+26.0%
Lagoon Pond lower Basin	LGP-9	0.328	0.338	+26.2%
West Arm (South End Basin)	LGP-10	0.378	0.401	+25.6%

VI.2.6.2 No Anthropogenic Load

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

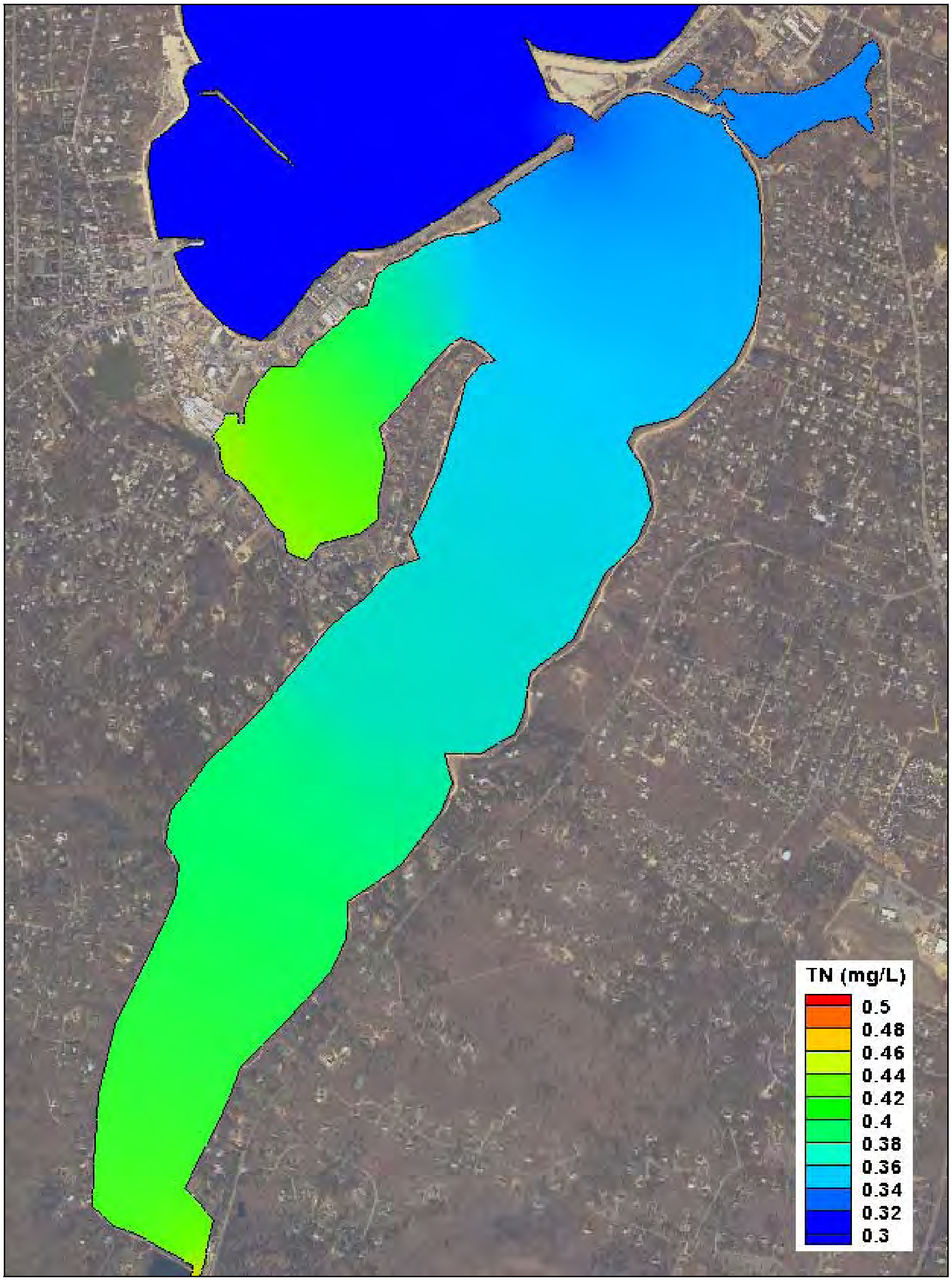


Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Lagoon Pond system, for projected build-out scenario loading conditions.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Lagoon Pond	1.827	7.156	19.279
West Arm (South End Basin)	0.164	0.921	5.784
Upper Lagoon Pond Stream	0.529	-	-
System Total	2.521	8.077	25.063

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations at each monitoring station. Again, total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was large (Table VI-8), with all areas of the system experiencing typical reductions greater than 62%, compared to the background concentration of 0.290 in Vineyard Haven Harbor. A contour plot showing TN concentrations throughout the system is shown pictorially in Figure VI-9.

Table VI-8. Comparison of model average total N concentrations from present loading and the "**No anthropogenic loading**" ("no load"), with percent change over background in Nantucket Sound (0.294 mg/L), for the Lagoon Pond system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	no-load (mg/L)	% change
Lagoon Pond head at dike	LGP-6	0.413	0.331	-66.7%
Lagoon Pond Head	LGP-4	0.385	0.325	-63.3%
Lagoon Pond upper Basin	LGP-2	0.371	0.320	-63.3%
Lagoon Pond mid Basin	LGP-8	0.338	0.307	-64.0%
Lagoon Pond lower Basin	LGP-9	0.328	0.304	-64.4%
West Arm (South End Basin)	LGP-10	0.378	0.323	-62.4%

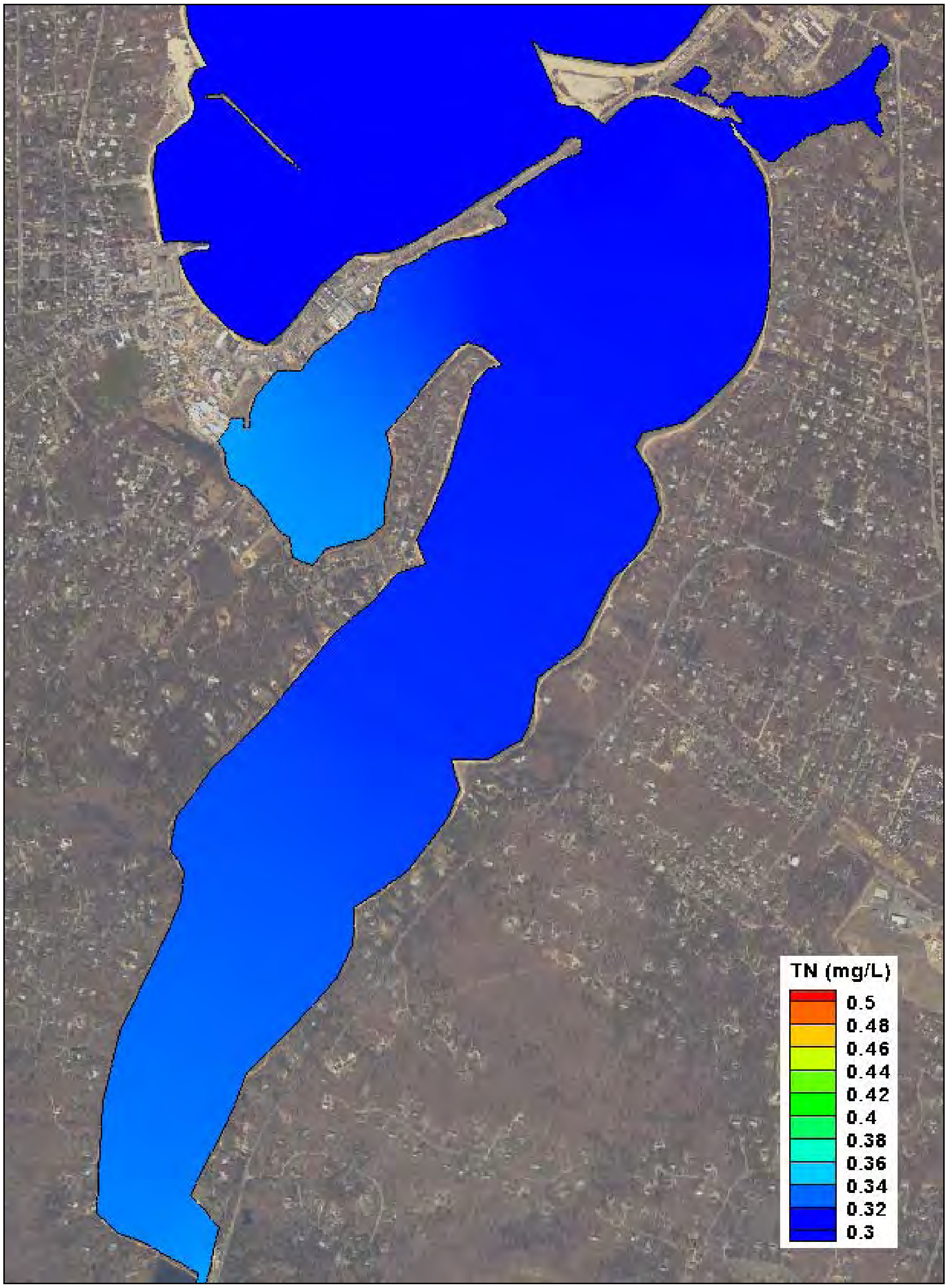


Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in Lagoon Pond, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Lagoon Pond embayment system in the Towns of Oak Bluffs and Tisbury, MA, the assessment is based upon: 1) data from the water quality monitoring baseline developed by the Martha's Vineyard Commission, the Towns and SMAST staff, 2) surveys of eelgrass distribution, 3) benthic animal communities and sediment characteristics and 4) dissolved oxygen records conducted during the summer and fall of 2004. These data form the basis of the assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for these systems (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen threshold determination, 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 Lagoon Pond at points that would be representative of dissolved oxygen conditions in the main Lagoon Pond basin, namely the upper and lower portions of the East Arm. 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 Lagoon Pond system was conducted to assess recent temporal trends in coverage (MassDEP Eelgrass Mapping Program, C. Costello). These coverages were compared to an earlier investigation using different methodology, to further evaluate changes in eelgrass coverage (Poole 1988). 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 Lagoon Pond system, temporal changes in eelgrass distribution provided a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet) in nutrient enrichment.

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

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 4.0 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 Lagoon Pond system are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality. It is through the MEP and TMDL processes that management actions are developed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within the upper and lower regions of the Lagoon Pond system (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September during the summer of 2003.

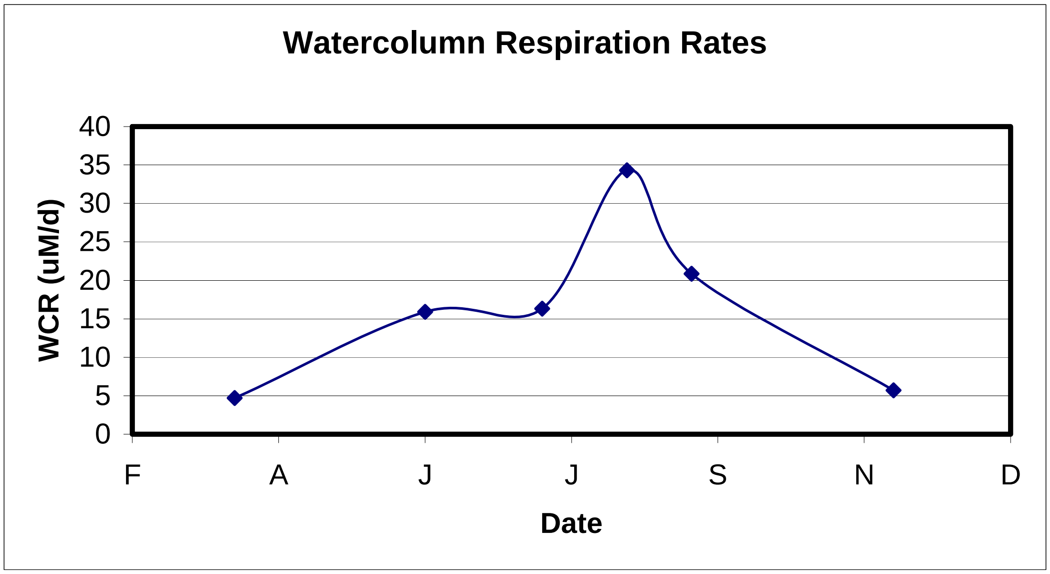


Figure VII-1. Average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Lagoon Pond system evaluated in this assessment showed high frequency variation, apparently related to diurnal and sometimes tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration within the upper pond along with periodic anoxia 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 33 to 51 day (Lagoon Pond lower and Lagoon Pond upper respectively) 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.

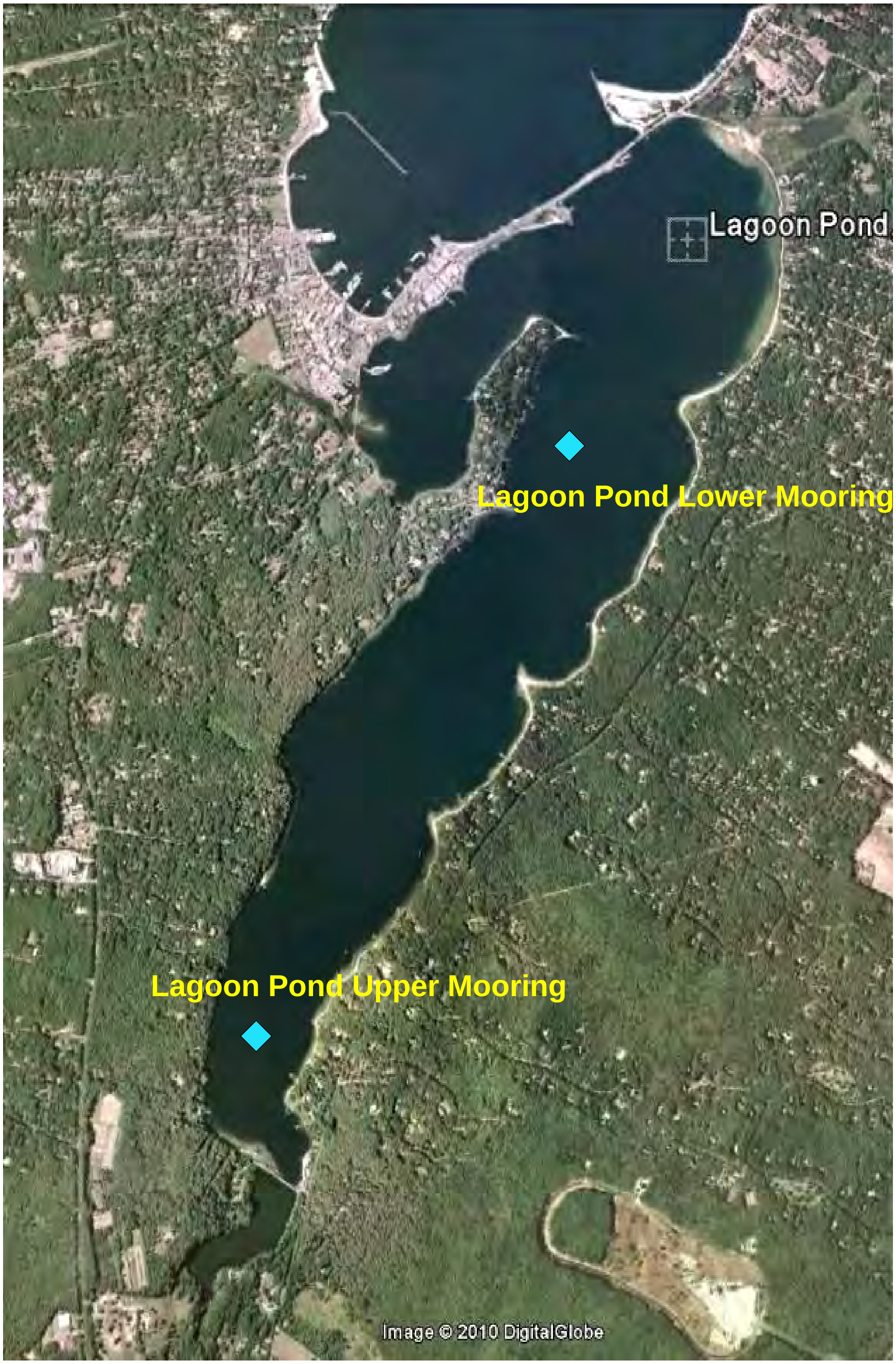


Figure VII-2. Aerial Photograph of the Lagoon Pond system in the Towns of Oak Bluffs and Tisbury showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2003.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate conditions of poor habitat quality at the mooring sites (Figures VII-3 through VII-6). The chlorophyll-*a* levels indicate only moderate nitrogen enrichment, while the bottom water oxygen levels show prolonged hypoxia and periodic anoxia at both locations. It is likely that the basins which comprise much of the bottom habitat of Lagoon Pond are not vertically well mixed during the summer which allows the moderate level of nutrient enrichment to produce very low oxygen conditions on a frequent basis. The oxygen data are 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 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 Lagoon Pond is magnified by its basin structure, which when combined with the depositional nature of the basins (as evidenced by the accumulations of drift macroalgae) and periodic reduced vertical mixing, results in poor quality benthic animal habitat within the deeper waters of the basins of the Eastern Branch. The lack of eelgrass in these areas is almost certainly a result of their depth (4-10 meters). Early surveys in Lagoon Pond and in other estuaries in the region generally do not show eelgrass beds at depths of more than 2-3 meters (<10'). It should be noted that the periods of reduced vertical mixing result from weak salinity stratification, where surface waters are ~1 ppt "fresher" than mid and 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.

Measured dissolved oxygen depletion indicate that the southern (upper) region of Lagoon Pond and the northern (lower) region show high to more moderate levels of oxygen stress respectively. The most prolonged hypoxia was observed in the head of Lagoon Pond (upper), which receives a significant portion of the watershed load and also is comprised of a deep basin that is prone to oxygen depletions in the deeper waters. This is seen clearly in the data record collected from the mooring deployed in that region of the system. 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, elevated chlorophyll-*a* and nitrogen levels are consistent with the observed pattern of eelgrass loss (Section VII.3). Although eelgrass is confined to the shallow margins within the East Arm of the estuary, its pattern of temporal loss is consistent with an estuarine system that is beyond its ability to assimilate nitrogen loads without impairment. Similarly, infaunal habitats (Section VII.4) also appear to be impaired by nitrogen enrichment, but the level of habitat impairment appears to be larger in deep versus shallow water. The embayment specific results are as follows:

Upper Lagoon Pond (south) (Figures VII-3 and VII-4):

The Lagoon Pond upper mooring site was centrally located within the main deep basin which dominates this region of the Lagoon Pond system (Figure VII-2). Generally, the daily excursions in oxygen levels at this location were moderate in that the range of the excursions was not wide. However, what was significant was that the oxygen levels ranged from levels only slightly in excess of air equilibration to periods of hypoxia approaching 0.0 mg L-1, a sign of a clearly oxygen stressed environment. The approximately 10 day gap in the oxygen record between August 16 and August 26 is due to the removal of extremely erratic data which most likely resulted from prolonged near anoxic conditions. Oxygen varied with light (diurnal cycle) and the tides. Lowest oxygen was generally observed in the early morning. Highest dissolved oxygen was observed when low tide occurred at the end of the photocycle (ca. 1500 hrs). Oxygen levels were almost always less than 6 mg L^{-1} and 38% of the 43 day record was less than 3 mg L^{-1} (Table VII-1, Figure VII-3). Oxygen levels did not show levels in excess of air equilibration with any frequency. Chlorophyll-*a* indicated periodic blooms of phytoplankton where levels increased from a baseline of ~4 ug L^{-1} to ~12 ug L^{-1}. These multiple phytoplankton bloom events were not observed in the lower basin of the pond. Interestingly, at the Lagoon Pond upper (southern) mooring location, chlorophyll-*a* levels never exceeded the 15 ug L^{-1} benchmark and only exceeded the 10 ug L^{-1} benchmark 5% of the time (Table VII-2, Figure VII-4). Average chlorophyll levels over 10 ug L^{-1} have been used to indicate eutrophic conditions in embayments.

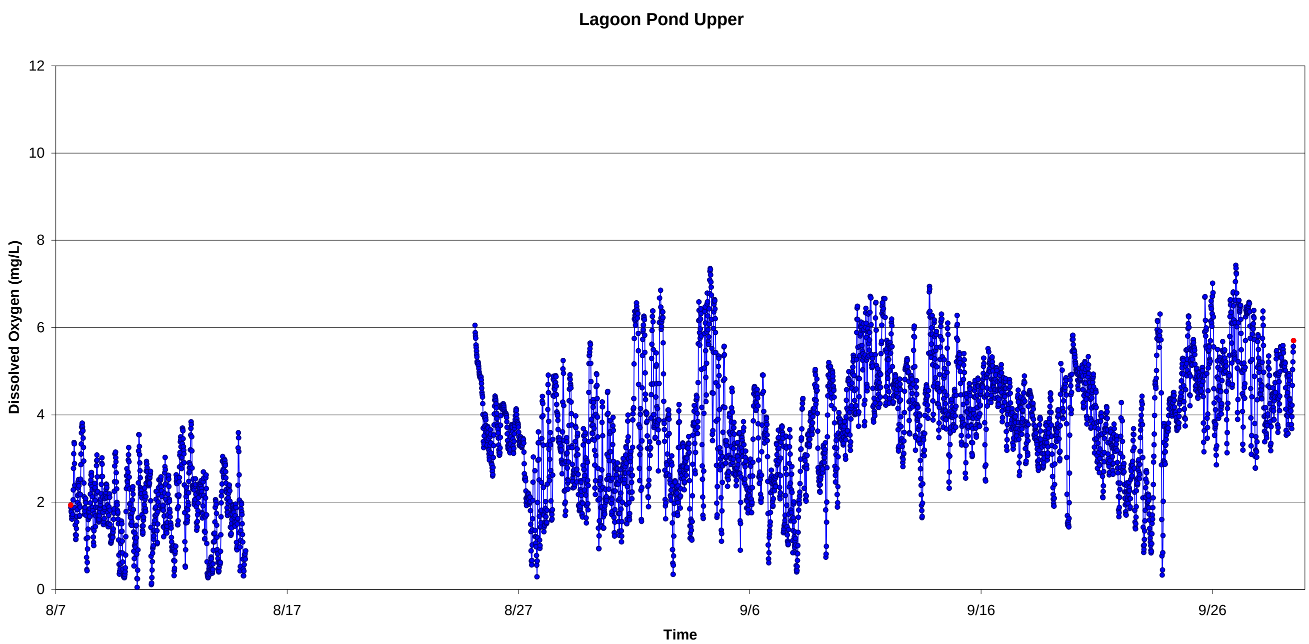


Figure VII-3. Bottom water record of dissolved oxygen at the Lagoon Pond upper station, Summer 2003 (Figure VII-2). Calibration samples represented as red dots.

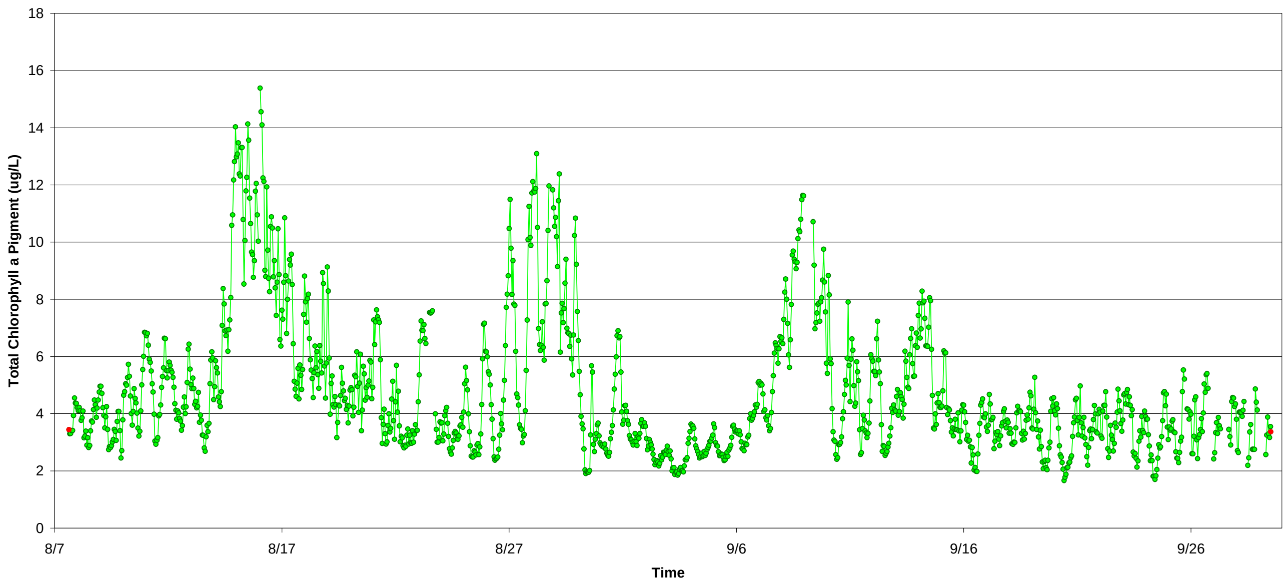


Figure VII-4. Bottom water record of Chlorophyll-*a* in the Lagoon Pond upper station, Summer 2003. Calibration samples represented as red dots.

Lower Lagoon Pond (north) (Figures VII-5 and VII-6):

The Lagoon Pond lower mooring site was centrally located within the main basin of Lagoon Pond at the northern end approximately 1.0 km from the main inlet transporting high quality low nutrient waters into the system from Vineyard Sound via Vineyard Haven Harbor (Figure VII-2). Generally, the daily excursions in oxygen levels at this location were small, in contrast to the excursions observed at the Lagoon Pond upper location. Oxygen did vary with light (diurnal cycle) and the tidal cycle, but the influence was small compared to the low frequency variation of periods of hypoxia/anoxia and air equilibration. Since there is a relatively low level of phytoplankton productivity as represented by low chlorophyll-*a* levels in this basin, it is likely that the low frequency variation (over many days) results from periods of reduced vertical mixing allowing the high rates of sediment and water column oxygen demand to lower bottom water oxygen levels. Oxygen levels frequently declined to <6 mg L^{-1} with multi-day periods <4 mg L^{-1}. Over the 33 day record, 14% of the time showed values below 3 mg L^{-1} (Table VII-1, Figure VII-5).

Chlorophyll-*a* levels at both the upper and lower mooring sites are consistent with the observed level of nitrogen enrichment. Nitrogen enrichment is moderate, 0.384 mg L^{-1} and 0.333 mg L^{-1}, for the upper and lower basins as are the average chlorophyll-*a* levels, 4.8 ug L^{-1} and 3.4 ug L^{-1}, and much larger and frequent blooms (to ~12 ug L^{-1}) in the upper basin. In contrast the level of oxygen depletion is much greater than is typical of shallow water systems with these nitrogen and chlorophyll-*a* levels. This is expected given the observed periodic reduction in vertical mixing by the weak salinity stratification of waters in these deep basins. The effect of the geomorphology of Lagoon Pond's basins is to increase deposition of organic matter (increasing oxygen uptake from bottom waters) and "isolate" 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. This contrasts with the pattern of eelgrass loss (see below), which is a shallow water phenomenon that appears to be directly linked to nitrogen enrichment.

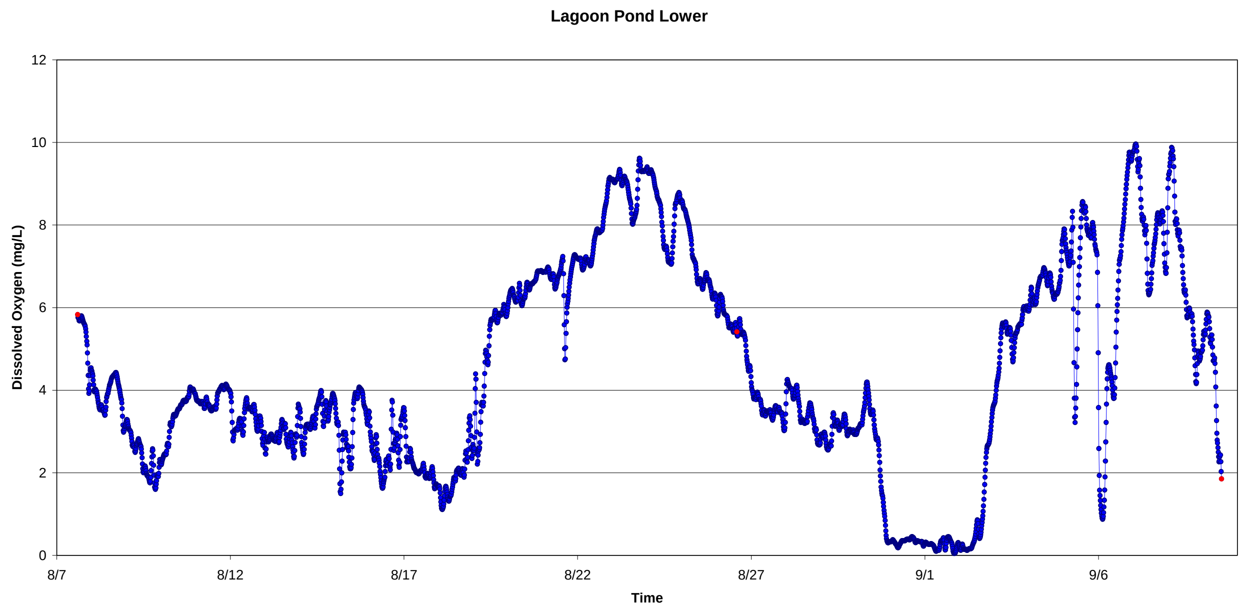


Figure VII-5. Bottom water record of dissolved oxygen at the Lagoon Pond lower station, Summer 2003 (Figure VII-2). Calibration samples represented as red dots.

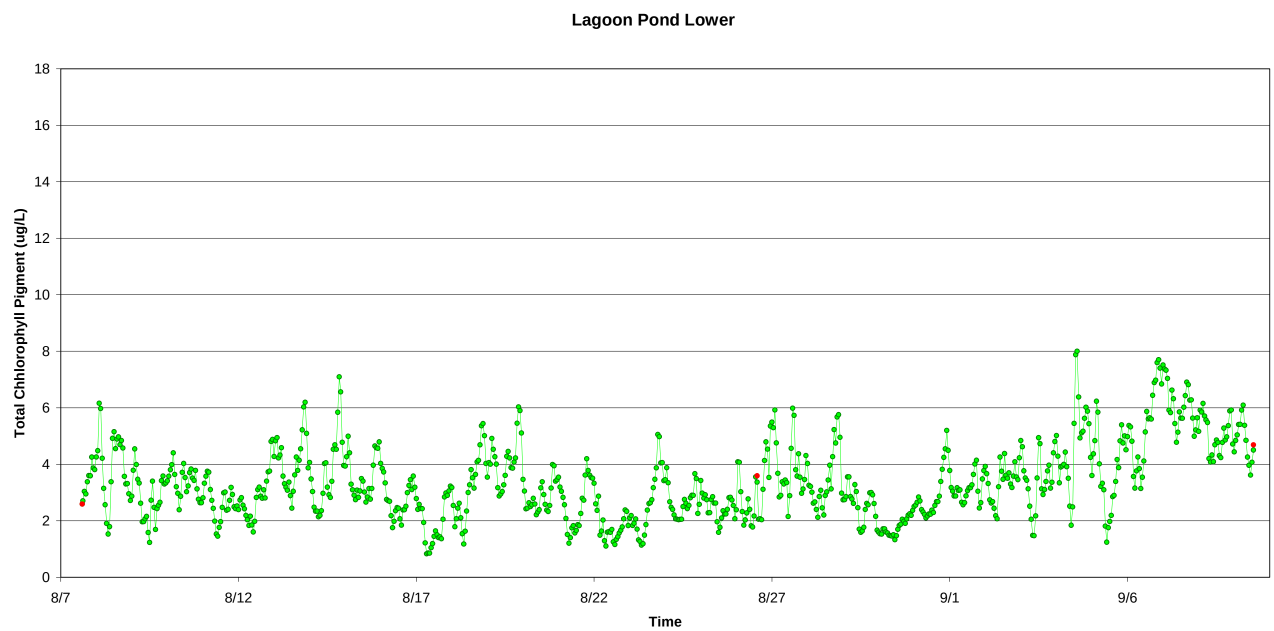


Figure VII-6. Bottom water record of Chlorophyll-*a* in the Lagoon Pond lower station, Summer 2003. Calibration samples represented as red dots.

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)
Lagoon Pond Lower	**8/7/2003**	**9/9/2003**	**33.0**	**57%**	**48%**	**26%**	**14%**
			Mean	2.36	0.83	0.45	0.38
			Min	0.01	0.01	0.02	0.03
			Max	11.45	3.32	3.04	2.94
			S.D.	3.98	1.09	0.77	0.82
Lagoon Pond Upper	**8/7/2003**	**9/29/2003**	**42.9**	**94%**	**84%**	**62%**	**38%**
*note 10 day gap in record not included in calculations			Mean	0.94	0.47	0.27	0.16
Data was erratic during this period.			Min	0.01	0.01	0.01	0.01
It is likely that the data discontinuity resulted			Max	8.53	7.51	7.51	1.32
from anoxia, but the true duration cannot be determined			S.D.	2.09	1.11	0.74	0.21

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)
Lagoon Pond Lower	**8/7/2003**	**9/9/2003**	**33.0**	**12%**	**0%**	**0%**	**0%**	**0%**
Mean Chl Value = 3.4 ug/L			Mean	0.16	N/A	N/A	N/A	N/A
			Min	0.04	0.00	0.00	0.00	0.00
			Max	0.88	0.00	0.00	0.00	0.00
			S.D.	0.18	N/A	N/A	N/A	N/A
Lagoon Pond Upper	**8/7/2003**	**9/29/2003**	**51.1**	**32%**	**5%**	**0%**	**0%**	**0%**
Mean Chl Value = 4.8 ug/L			Mean	0.37	0.20	0.04	N/A	N/A
			Min	0.04	0.04	0.04	0.00	0.00
			Max	3.17	0.54	0.04	0.00	0.00
			S.D.	0.64	0.16	N/A	N/A	N/A

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data was conducted for the Lagoon Pond Embayment System by the MassDEP Eelgrass Mapping Program as part of the MEP. Surveys were conducted in 1995, 2001 and 2006, as part of this program. Additional analysis of available aerial photos from 1951 was not possible to reconstruct the eelgrass distribution prior to any substantial development of the watershed as the 1951 aerial photographs were not of sufficient quality. However, an eelgrass survey from 1987, conducted as part of a diagnostic feasibility study (Poole 1988) provided useful information for qualitative comparison to the 1995 MassDEP survey results. The 1995 and 2001 maps were field validated. The primary use of the data are to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1987 to 2006 (Figures VII-7a+b); 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 exists mainly within the lower portion of the Lagoon Pond system closest to the inlet, with narrow beds in the shallow water margins fringing the basins within the central (mid) and upper (south) basins of the East Arm (Figure VII-7a). Upper refers to up-gradient (up the hydrologic gradient) and lower refers to down gradient (down the hydrologic gradient). There is no eelgrass present in the semi-enclosed West Arm, although there may have been a small shallow water patch in 1987 (Figure VII-7b). It appears that eelgrass is generally present at depths <2 meters, consistent with observed light penetration data from the water quality monitoring program (average Secchi depths of ~3 m). The observed light penetration data are consistent with the observed water quality data and supports the contention that the absence of eelgrass from the deep basins (4-10 meters) is primarily due to insufficient light.

The absence of eelgrass within the West Arm of the estuary is based on the 1995 and 2001 eelgrass surveys completed by the MassDEP, with intensive field validation and additional validation in 2003 by multiple MEP staff conducting infaunal animal and sediment sampling and mooring studies. The absence of eelgrass in this basin is consistent with its level of nitrogen enrichment (monitoring average, 0.386 mg N L^{-1}) which is on the same order as the upper basin of the East Arm (monitoring average, 0.386 mg N L^{-1}) which has also lost its fringing eelgrass, while the eelgrass beds that persist are in areas with significantly lower nitrogen levels. The 2006 MassDEP survey showed a continuing reduction in eelgrass area within Lagoon Pond, with continuing loss of beds from the upper basin and losses of bed area 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 Lagoon Pond, as well.

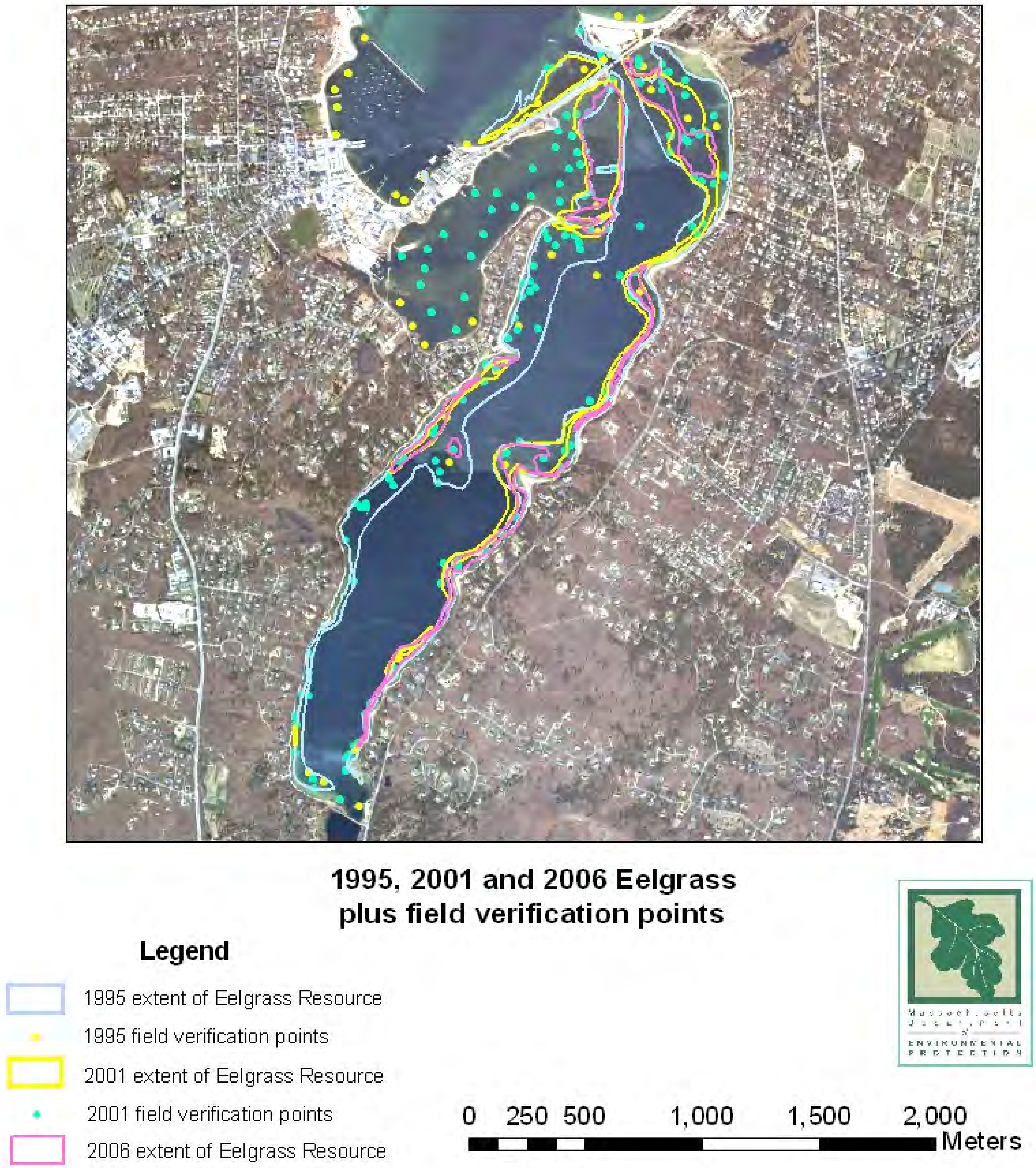


Figure VII-7a. Eelgrass bed distribution within the Lagoon Pond System. The 1995 coverage is depicted by the grey outline which circumscribes the eelgrass beds, similarly the 2001 (yellow line) and 2006 (magenta line). Eelgrass areas were surveyed by the MassDEP Eelgrass Mapping Program (C. Costello).

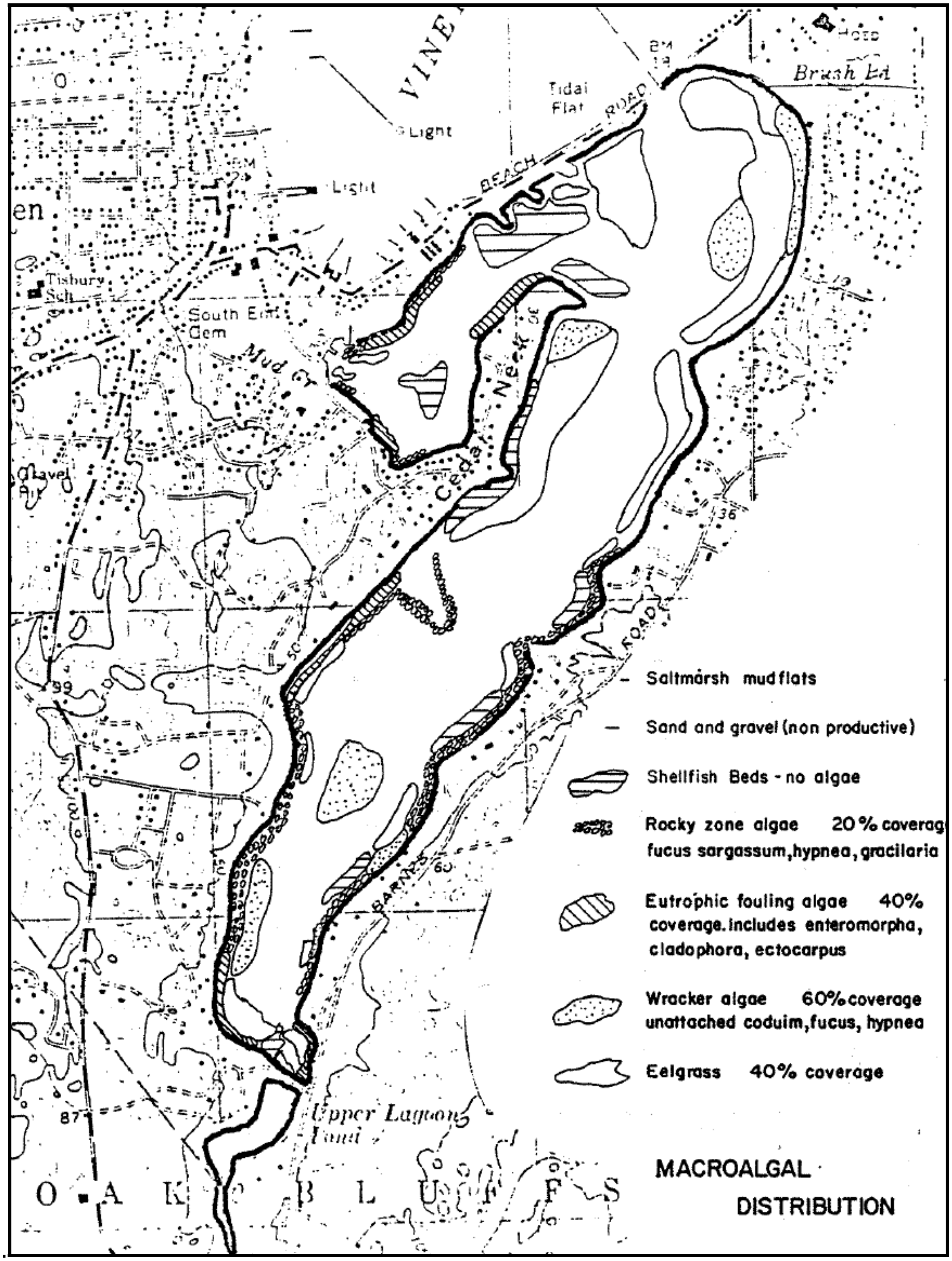


Figure VII-7b. Eelgrass bed and macroalgal distribution within the Lagoon Pond System in 1987 (Poole 1988). Eelgrass areas extend the length of the Pond in the 1995 survey by the MassDEP Eelgrass Mapping Program (Figure 7a), although they are more discontinuous.

The persistence of fringing beds in the upper basin suggests that nitrogen enrichment is moderate, 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 fringing beds 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 deep basins of the East Arm and virtually all of the West Arm ever having had eelgrass habitat, establishment of eelgrass in these basins cannot be supported as a specific restoration goal.

Other factors which influence eelgrass bed loss in embayments can also be at play in the Lagoon Pond Embayment System, though the recent loss appears completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density as the areas with observed bed loss do not support permanent boat mooring areas. While pier construction can cause impacts to eelgrass beds, there are few piers on the shores of Lagoon Pond and the majority are small structures associated with private homes. On the other hand, 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, especially given the structure of the basins, East Arm being relatively deep and the West Arm being very shallow and never having shown eelgrass in the past. It is possible that since the majority of Lagoon Pond is approved for shellfishing 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 minimum eelgrass bed area that might be recovered is on the order of 113 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 Lagoon Pond in 1951. Note that restoration of this eelgrass habitat will necessarily result in restoration of other resources throughout the Lagoon Pond 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 Lagoon Pond Embayment System within the Towns of Oak Bluffs and Tisbury over the past 15 years (MassDEP, C. Costello).

Lagoon Pond Embayment System: Temporal Change in Eelgrass Coverage					
Embayment	**1951 (acres)**	**1995 (acres)**	**2001 (acres)**	**2006 (acres)**	**Percent Difference (1995 to 2006)**
Lagoon Pond	NA	164.57	72.68	51.36	**69%**

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling for benthic community characterization was conducted at 10 locations throughout the Lagoon Pond 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, 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 Lagoon Pond System is clearly impaired by nutrient overloading. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). In addition, it is necessary to evaluate infauna habitat information relative to the geomorphology of the Lagoon Pond basins and their periodic weak stratification that increases the potential for impaired habitat. 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, ≥4 meters, are not supportive of infaunal communities. The large areas of bottom at these depths have significantly degraded (extremely poor) habitat for infaunal animals. The communities are depauperated with few individuals and species that appear to represent the continuous re-introduction of new individuals. The deep basins of the entire East Arm of Lagoon Pond averaged < 30 individuals per sample compared to the 500-1000 that is typical of high quality benthic habitat. At these low population levels, Diversity and Evenness are irrelevant, the major finding being the lack of a community. In contrast the shallow waters (~1 meter) of the West Arm (West Arm (South End Basin)) had high individuals (dominated by crustaceans) and diversity with moderate numbers of species and evenness. These values are indicative of a productive, but moderately impaired habitat. It is virtually certain that the narrow marginal areas of the East Arm have similar habitat quality to that of the West Arm.

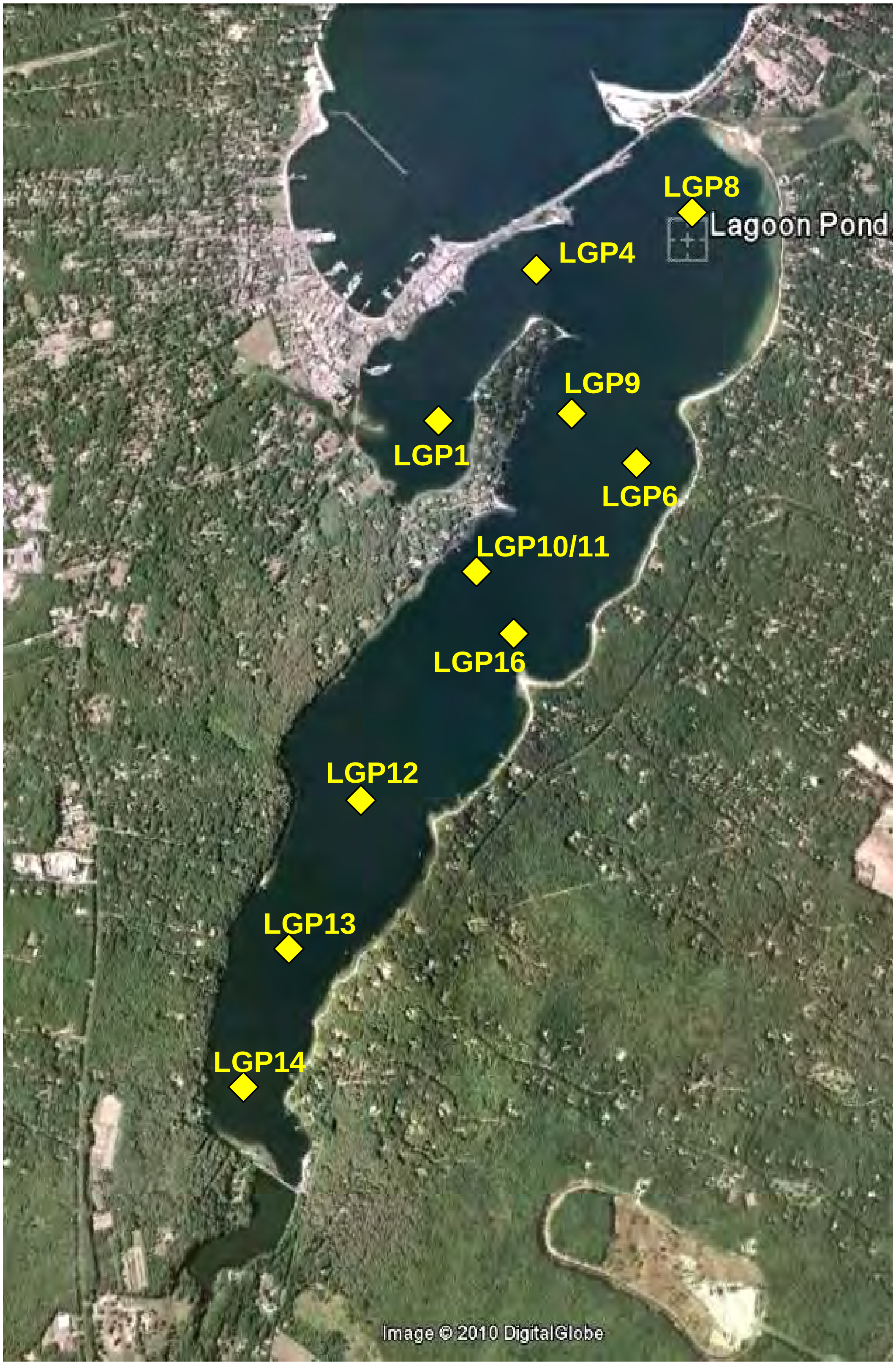


Figure VII-8. Aerial photograph of the Lagoon Pond system showing location of benthic infaunal sampling stations (blue symbol).

The chlorophyll-*a* and nitrogen levels of the entirety of Lagoon Pond are consistent with moderate to high quality habitat in shallow basins throughout southeastern Massachusetts. Nitrogen enrichment is moderate, 0.384 mg L^{-1} and 0.333 mg L^{-1}, as are the average chlorophyll-*a* levels, 4.8 ug L^{-1} and 3.4 ug L^{-1}. As discussed above, it is the extent of periodic summertime oxygen depletion resulting from the periodic reduction in vertical mixing due to the weak salinity stratification of water column that causes the lack of infauna in these deep basins. The effect of the geomorphology of the basins of Lagoon Pond is an increase in the deposition of organic matter (increasing oxygen uptake from bottom waters) in 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. It should be noted that the extent of the hypoxia/anoxia at low nitrogen enrichment (in the basins adjacent the inlet) suggests that without a change in basin configuration, nitrogen management alone will not raise these areas to high quality infauna habitat, though they will likely improve over present conditions. The infaunal habitat assessment contrasts with the eelgrass assessment (Section VII-3), which is a shallow water phenomenon where restoration can occur through nitrogen management.

Overall, the infaunal habitat quality in Lagoon Pond and the west arm of Lagoon Pond was consistent with the data collected on levels of dissolved oxygen, chlorophyll, nutrients and organic matter enrichment and basin structure within each component of the system. Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to whether it was dominated by wetlands or more so representative of a tidal embayment with a potential for stratification due to depth. Based upon this analysis it is clear that the tributary sub-embayment basin of the west arm of Lagoon Pond is presently supporting moderately impaired benthic habitat, while the main basin of Lagoon Pond system (East Arm) is generally showing signs of significant degradation (very poor quality), partially due to depth and basin geomorphology. It should be noted that habitat quality of the East Arm of Lagoon Pond is best indicated by eelgrass habitat and the West Arm by benthic community characteristics, and that restoring these habitats should be the focus of the nitrogen management threshold analysis (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 (Table VII-4). 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 Lagoon Pond system are approved for the taking of shellfish year round. Only a small portion of the west arm of Lagoon Pond is conditionally approved for the taking of shellfish during specific times of the year, typically the cold winter months, indicating the system is generally supportive of healthy shellfish communities. The major shellfish species with potential habitat within the Lagoon Pond 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 Lagoon Pond system along the fringe (Figure VII-8). In addition, if habitat conditions improve there is also the potential for significant grow areas for soft shelled clams to develop throughout the system. However, the map indicates the potential for shellfish growing and does not account for the deep basins within the pond which have likely had periodic hypoxia for a long time and are presently not supportive of shellfish. The margins around the deep water basins support the best infauna (shellfish) habitat.

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 LPG -
Lagoon Pond - Eastern Branch						
South (upper) Basin	2	4	--[1]	1.41	0.96	13,14
Central (mid) Basin	5	27	6	1.72	0.79	10,12,16
North (lower) Basin	6	29	--[1]	1.79	0.82	6,8,9
Lagoon Pond - Western Branch						
South End Basin	19	794	11	2.51	0.61	1,4

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

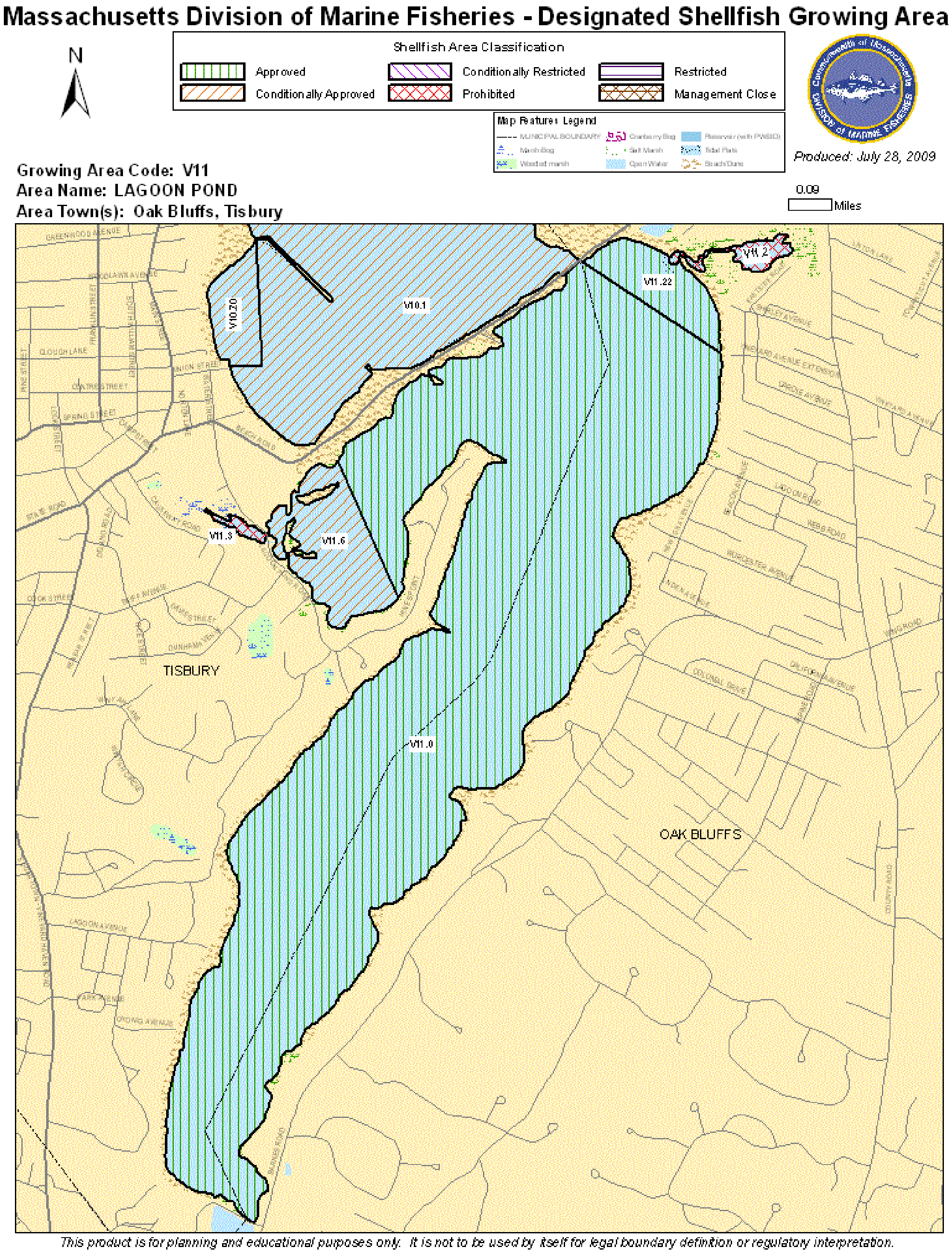


Figure VII-9. Designated shellfish growing areas and status of closures within the Lagoon Pond system, Town of Oak Bluffs and Tisbury, MA. Source: Massachusetts Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

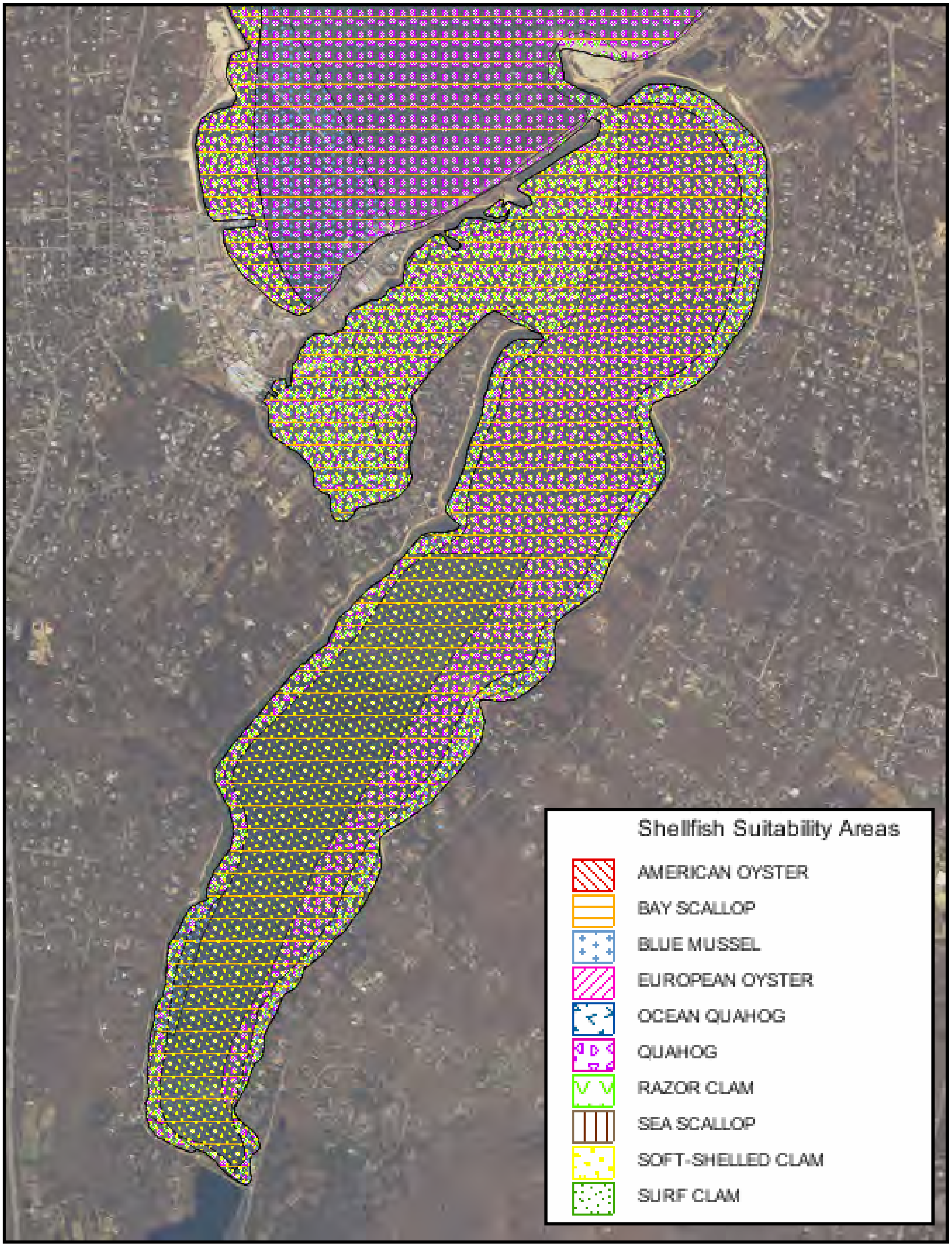


Figure VII-10. Potential shellfish growing areas within the Lagoon Pond system, Town of Oak Bluffs and Tisbury, MA. Primary species with potential suitable habitat are soft shell clams and quahogs. Note: Suitability does not necessarily mean "presence", for example, the deep basins do not presently support 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 Lagoon Pond Embayment System by the MEP and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline the Water Quality Monitoring Program conducted by the Martha's Vineyard Commission and the Towns of Oak Bluffs and Tisbury, with technical and analytical support from the Coastal Systems Program at SMAST-UMass Dartmouth.

The Lagoon Pond Embayment System is a simple estuary formed as a composite due to the drowning of a valley (upper reaches) and a lagoon forming the lower reach. This was precipitated as a result of the development of a barrier beach across the entrance. Lagoon Pond is composed of a single functional type of basin: an open water embayment with multiple deep basins (up to 10 meters depth) that periodically develop weak salinity stratification and bottom water oxygen depletion. There is a single stream inflow to the headwaters of the major tributary sub-embayment (East Arm). Each type of functional component (salt marsh basin, embayment, tidal river, deep basin {sometimes drowned kettles}, shallow basin) 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 Lagoon Pond 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 system is showing some nitrogen related habitat impairment throughout its tidal reaches. The East Arm, which forms the main body of Lagoon Pond, is comprised of multiple deep basins with the lower basin within the lagoon behind the barrier beach also relatively deep (8 m). The East Arm historically has supported fringing eelgrass beds, presumably due to the limitation of the depth of eelgrass growth by light limitation in the deep basins. While fringing eelgrass beds are still found in each of the basins of the East Arm, their coverage is being reduced to shallower areas and also being disproportionately lost in the upper and mid basins. 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 by the MEP for these areas. The West Arm has not historically supported stable eelgrass beds. At present the infaunal communities are moderately impaired. However, given the level of impairment and the location of this basin within the Lagoon Pond System, it is certain that restoring eelgrass habitat within the upper basin will result in restoration of this infaunal habitat, as nitrogen enrichment will be significantly reduced to the overall estuary (Section VIII.3).

Eelgrass: At present, eelgrass exists mainly within the lower portion of the Lagoon Pond system closest to the inlet, with narrow beds in the shallow water margins fringing the basins within the central (mid) and upper (north) basins of the East Arm (Section VII, Figure 7a). There is no eelgrass present in the semi-enclosed West Arm, although there may have been a small shallow water patch in 1987 (Section VII, Figure 7b). It appears that eelgrass is generally restricted to depths <2 meters, consistent with observed light penetration data from the water quality monitoring program (average Secchi depths of ~3 m). The observed light penetration data are consistent with the observed water quality data and supports the contention that the absence of eelgrass from the deep basins (4-10 meters) is primarily due to insufficient light. Additionally, shallow narrow eelgrass beds extend upwards towards the head of the system along the shoreline.

Eelgrass bed coverage within Lagoon Pond has been declining since 1995 (possibly even back to 1987). The pattern of bed loss showing "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 Lagoon Pond, as well. However, the persistence of fringing beds in the upper basin suggests that nitrogen enrichment is moderate, which is also consistent with the observed chlorophyll-*a* levels. The continuous losses of bed area from 1995-2006 indicate that habitat decline and nitrogen enrichment is continuing.

As eelgrass within Lagoon Pond 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 the Lagoon Pond Embayment System. It should be noted that since there is little evidence of the deep basins of the East Arm and virtually all of the West Arm ever having had eelgrass habitat, establishment of eelgrass in these basins cannot be supported as a specific restoration goal. Nutrient management planning for restoration of the fringing eelgrass habitat within the basins of the East Arm of Lagoon Pond should focus on reducing the level of nitrogen enrichment in basin waters through watershed nitrogen management and/or increases in tidal exchange as appropriate.

The absence of eelgrass within the West Arm 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. In contrast, some stable eelgrass beds were observed within the lower basin at tidally averaged nitrogen levels of 0.328 mg N L^{-1}, while fringing eelgrass beds presently exist in the shallow margins of the upper and mid basin at nitrogen levels between 0.371 mg N L^{-1} and 0.338 mg N L^{-1}.

Nitrogen levels associated with persistence and loss of eelgrass in waters ~2 meters in depth are lower than found for high quality habitat in shallow water (<1 meter). 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}. These levels of enrichment are similar to those found in the present assessment of Lagoon Pond.

Based upon the above analysis, eelgrass habitat was selected as the primary nitrogen management goal for the Lagoon Pond 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 Lagoon Pond prior to 1995. It does appear that the 113 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 Lagoon Pond 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 East Arm 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 management alternatives analysis presented in Chapter IX.

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

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate conditions of poor habitat quality within the deep basin waters (>4 meters) of Lagoon Pond under moderately nutrient enriched conditions. The chlorophyll-*a* levels also indicate only moderate nitrogen enrichment, while the bottom water oxygen levels show prolonged hypoxia and periodic anoxia in deep waters. It appears that the basins which comprise much of the bottom habitat of Lagoon Pond are periodically not vertically well mixed during the summer, which allows the moderate level of nutrient enrichment to produce very low oxygen conditions on a frequent basis. The oxygen data are 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 follow the spatial pattern of total nitrogen levels in this system. It is clear that the nutrient enrichment response in Lagoon Pond 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 basins of the Eastern Branch. The lack of eelgrass in these areas is almost certainly a result of their depth (4-10 meters), as early surveys in Lagoon Pond and in other estuaries in the region generally do not show eelgrass beds at depths of more than 2-3 meters (<10'). It should be noted that the periods of reduced vertical mixing result from weak salinity stratification, where surface waters are only ~1 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 observed gradient in nitrogen enrichment and chlorophyll-*a* levels is consistent with the pattern of eelgrass habitat decline throughout the estuary and indicate only a moderate level of nitrogen enrichment. However, given the structure of the estuary, eelgrass is becoming restricted to shallower depths, resulting in loss of habitat primarily within the upper and mid basins of the Eastern Arm of Lagoon Pond. Management of nitrogen levels through reductions in watershed nitrogen inputs and increased tidal flushing, as appropriate, are required for restoration of eelgrass and infaunal habitats within the Lagoon Pond Embayment System.

Infaunal Communities: In all areas and particularly those that do not support eelgrass beds, benthic animal indicators are used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The survey of infauna communities throughout Lagoon Pond indicated a system presently supporting impaired benthic infaunal habitat in the shallow basin and degraded habitat within the deep basins as a result of periodic hypoxia/anoxia in summer.

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 the basins in Lagoon Pond is to increase deposition of organic matter (increasing oxygen uptake from bottom waters) and the "isolation" of 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. This contrasts with the pattern of eelgrass loss, which is a shallow water phenomenon that appears to be directly linked to nitrogen enrichment.

Overall, the infauna survey indicated that deeper areas ($\geq$4 meters) are not supportive of infaunal communities. The large areas of bottom at these depths have significantly degraded (extremely poor) habitat for infaunal animals. The communities were composed of few individuals and species that appear to represent the continuous re-introduction of new individuals. The deep basins of the entire East Arm of Lagoon Pond averaged < 30 individuals per sample compared to the 500-1000 typical of high quality benthic habitat. At these low population levels, diversity and Evenness is irrelevant, the major finding being the lack of a community. In contrast the shallow waters (~1 meter) of the West Arm (West Arm [South End Basin]) had high individuals (dominated by crustaceans) and diversity with moderate numbers of species and Evenness. These values are indicative of a productive, but moderately impaired habitat. It is virtually certain that the narrow marginal areas of the East Arm have similar habitat quality to that of the West Arm.

The infaunal habitat quality in the East and West Arms of Lagoon Pond was consistent with the observed levels of dissolved oxygen, chlorophyll, nutrients and organic matter enrichment as well as basin structure within each component of the system. The chlorophyll-*a* and nitrogen levels of the entirety of Lagoon Pond are consistent with moderate to high quality habitat in shallow basins throughout southeastern Massachusetts. Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to whether it was representative of a deep tidal embayment with a potential for stratification. Based upon this analysis it is clear that the tributary sub-embayment basin of the West Arm of Lagoon Pond is presently supporting moderately impaired benthic habitat, while the main East Arm of the Lagoon Pond system is generally showing signs of significant degradation of infaunal habitat (very poor quality), partially due to depth and basin geomorphology. It should be noted that habitat quality of the East Arm of Lagoon Pond is best indicated by eelgrass habitat and the West Arm by benthic community characteristics, and that restoring these habitats should be the focus of the nitrogen management threshold analysis (Section VIII.2). The extent of the hypoxia/anoxia at low nitrogen enrichment (even in the basin adjacent the inlet) suggests that without a change in basin configuration, nitrogen management alone will not raise these areas to high quality infauna habitat, although they will likely improve over present conditions. The infaunal habitat assessment contrasts with the eelgrass assessment, which is a shallow water phenomenon where restoration can occur through nitrogen management.

Table VIII-1. Summary of nutrient related habitat quality within the Lagoon Pond Estuary within the Towns of Oak Bluffs and Tisbury, MA, based upon assessments in Section VII. The main basin (East Arm) extends to the headwaters at Upper Lagoon Pond and consists of multiple deep basins (>4 m), while the West Arm is semi-enclosed and shallow (~1 m). WQM indicates: the Lagoon Pond Water Quality Monitoring Program (2002-2007).

Health Indicator	Lagoon Pond Embayment System			
	East Arm (Branch)			West Arm (Branch)
	South Basin (upper)	Central Basin (mid)	North Basin (lower)	
Dissolved Oxygen	SI[1]	SI[2]	SI[3]	MI[4]
Chlorophyll	MI[5]	MI[6]	H[7]	H[8]
Macroalgae	MI[9]	MI[9]	H[10]	MI[9]
Eelgrass	SI[11]	SI[11]	MI[12]	'--[13]
Infaunal Animals	SD[14]	SD[14]	SD[14]	MI[15]
Overall:	**SI[16]**	**SI[16]**	**SI[16]**	**MI[17]**

1 – oxygen depletion in basins frequently <4 mg/L, <3 mg/L 38% of time.
2 – oxygen status based upon flanking upper and lower basins and with similar depth and water quality.
3 – oxygen depletion in basin frequently <4 mg/L with periods of anoxia.
4 – oxygen minimum 4.7 mg/L from 2002-2007 WQM, 80% of samples >6 mg/L.
5 – moderate summer chlorophyll levels generally <8 ug/L, averaging 4.8 ug/L, average level in summer WQM samples (2002-2007) was ~5 ug/L.
6 – moderate summer chlorophyll levels similar to South Basin (upper) average level in summer WQM samples (2002-2007) was ~5 ug/L.
7 – low summer chlorophyll levels generally <5 ug/L (88% of time), averaging 4.8 ug/L, average level in summer WQM samples (2002-2007) was 4.4 ug/L.
8 – low summer chlorophyll levels similar to North Basin (lower) with average level in summer WQM samples (2002-2007) of 4.8 ug/L.
9 – patches of dense drift *Gracillaria*, deposited in deep basin, (south basin has patches of algal mat)
10 – patches of sparse *Gracillaria*, sparse attached *Codium*.
11 – MassDEP (C. Costello) indicates that eelgrass coverage significantly declined 1995-2006.
12 – MassDEP (C. Costello) and Poole (1988) maps indicate that while some eelgrass beds are "stable", 1995-2006, decline in coverage has occurred primarily on the eastern side of the inlet channel.
13 – no evidence this basin has historically supported stable eelgrass beds, no eelgrass in MassDEP (C. Costello) assessments of 1995, 2001 and 2006.
14 – low numbers of individuals (<30 per sample) and low number of species, habitat not presently supporting an infaunal animal community in deep basin.
15 – high numbers of individuals and diversity, moderate species numbers and Evenness, with community dominated by crustaceans, some of which are found in organic enrichment areas.
16 – Significant Impairment: primarily due to significant reduction in eelgrass beds (1995-2006), periodic D.O. depletion & significantly degraded animal community habitat is confounded in the deep basin by periodic reductions in vertical mixing due to weak salinity stratification in deep water, with only moderate chlorophyll levels and low-moderate accumulation of drift macroalgae.
17 – Moderate Impairment: primarily due to the benthic community habitat assessment, moderate summer depletion in D.O, low summer chlorophyll levels and low-moderate accumulation of drift macroalgae. Since eelgrass is not recognized to have historically colonized this basin, infaunal habitat forms 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

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

The Lagoon Pond Embayment System presently supports nitrogen related habitat impairment throughout the tidal reach. Fringing eelgrass beds within the upper reach of the Eastern Arm of the estuary have declined significantly from 1995-2006. Since there is little evidence that the deep basins of the East Arm and the West Arm ever supported stable eelgrass habitat, establishment of eelgrass in these basins is not included as a specific restoration goal. In contrast the fringing beds in the Eastern Arm are well documented. Although these beds are declining, some eelgrass habitat still persists. The extent of the loss of this fringing eelgrass habitat resulted in the assessment of the eelgrass resources as "significantly impaired". Within the shallow Western Arm, infaunal habitat is presently moderately impaired by nitrogen and organic matter enrichment, while infaunal habitat within the deep basins of the Eastern Arm is virtually absent due to periodic hypoxia/anoxia resulting, in part, from the structure of this component of the system (discussed above and in Section VII-4). It should be noted that habitat quality of the East Arm of Lagoon Pond is best indicated by eelgrass habitat and the West Arm by benthic community characteristics. Restoring these habitats is the focus of the nitrogen management threshold analysis (Section VIII.3). The extent of the hypoxia/anoxia at low nitrogen enrichment (even in the basin adjacent the inlet) suggests that without a change in basin configuration, nitrogen management alone will not raise the deep basin degraded areas to high quality infauna habitat, although they will likely improve over present conditions.

As eelgrass within Lagoon Pond is a critical habitat structuring the productivity and resource quality of the entire system and it is presently showing impairment. As such, restoration of this resource is the primary target for overall restoration of the Lagoon Pond Embayment System. Nutrient management planning for restoration of the fringing eelgrass habitat within the basins of the East Arm of Lagoon Pond should focus on reducing the level of nitrogen enrichment in basin waters through watershed nitrogen management and/or increases in tidal exchange as appropriate.

The levels of TN and quality of the fringing eelgrass habitat observed in Lagoon Pond are comparable to similar deep (>2m) eelgrass habitat in the region, where at these TN levels the eelgrass is stressed and is just beyond its tolerance limit. Based upon the information above and in Section VII, given the depth of Lagoon Pond and its level of eelgrass impairment it appears that the system is presently slightly beyond its nitrogen threshold for sustainable eelgrass coverage. This assessment is based upon the distribution of the remaining eelgrass habitat, the observed loss of eelgrass from deeper water and from the margins of the upper and mid basins of the Eastern Arm and that the decline appears to be relatively recent.

The absence of eelgrass within the West Arm 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. In contrast, some stable eelgrass beds were observed within the lower basin at tidally averaged nitrogen levels of 0.328 mg N L^{-1}, while fringing eelgrass beds presently exist in the shallow margins of the upper and mid basin at nitrogen levels between 0.371 mg N L^{-1} and 0.338 mg N L^{-1}. These TN levels and habitat stability/decline are consistent with persistence and loss of eelgrass at similar depths in other estuaries on Vineyard/Nantucket Sound. In Waquoit Bay at similar depths, eelgrass was found to slowly decline at average TN concentrations of 0.395 mg L^{-1} (lower basin of Waquoit Bay) and was also lost from the Centerville River at a tidally averaged TN of 0.395 mg L^{-1}. In the West Falmouth Harbor Estuary on Buzzards Bay, eelgrass declined when nitrogen enrichment resulted in levels over 0.35 mg L^{-1}.

Therefore, it appears that the threshold for stable eelgrass habitat in Lagoon Pond must be less than 0.385 mg N L-1, as this is the present level and loss is continuing. Similarly, it appears that eelgrass beds presently exist in Lagoon Pond at nitrogen levels between 0.371 mg N L^{-1} and 0.338 mg N L^{-1}. However, at the higher end of this range some loss is continuing. Based upon these observations and those from other systems, a tidally averaged nitrogen threshold for Lagoon Pond of 0.35 mg N L-1 will allow restoration of the impaired eelgrass habitat. This threshold is similar to that for West Falmouth Harbor and Phinneys Harbor, and is focused in part on restoring eelgrass at depth (~2 m) as found historically. This threshold is for the sentinel station LGP-2, located at the upper extent of the major fringing beds observed in 1995. The historically noted small narrow beds between the sentinel station and the headwaters should also be restored as these were mainly restricted to the shallows. 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 in the Western Basin. All lines of evidence considered, the goal is to achieve the nitrogen target at the sentinel location and restore the historical eelgrass habitat within Lagoon Pond, also resulting in the restoration of infaunal habitat within the shallow sediments throughout the System. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations are discussed in Section VIII.3, below.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Lagoon Pond system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel station chosen for Lagoon Pond. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment. 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 47% 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 Lagoon Pond watershed results in a 38% reduction in total watershed nitrogen load. No load reduction was necessary for the watershed of the surface water stream input to the head of Lagoon Pond. 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-basin relative to background concentrations in Vineyard Sound, as discussed in Section VI.2.6.1.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. The percent change P over background presented in this table is calculated as:

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

where N is the nitrogen concentration at the indicated monitoring station for present and threshold conditions, and also in Nantucket Sound (background). To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN concentrations of 23% is required in the system.

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

The basis for the watershed nitrogen removal strategy utilized to achieve the embayment thresholds may have merit, since this sample nitrogen remediation effort is focused on watersheds where groundwater is flowing directly into the estuary. For nutrient loads entering the systems through surface flow, natural attenuation in freshwater bodies (i.e., streams and ponds) can help by significantly reducing the load that finally reaches the estuary. Presently, this attenuation is occurring in "surface water" inputs to the system (e.g., upper Lagoon Pond as connected via the fish ladder) due to natural ecosystem processes and the extent of attenuation being determined by the mass of nitrogen which discharges to that component of the overall system. 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.

Another management alternative that is available for the Lagoon Pond system is the possibility of adding culverts under the Beach Road causeway, which separates the West Arm (South End Basin) from Vineyard Haven Harbor. Culverts would allow direct tidal exchange between West Arm (South End Basin) and Vineyard Haven Harbor and potentially reduce the amount of watershed N load reduction necessary to achieve the target threshold concentrations. A culvert scenario is discussed in Chapter IX.

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

sub-embayment	present septic load (kg/day)	threshold septic load (kg/day)	threshold septic load % change
Lagoon Pond	27.581	13.790	-50.0%
West Arm (South End Basin)	4.770	2.385	-50.0%
Upper Lagoon Pond Stream	2.060	2.060	0.0%
System Total	34.411	18.236	-47.0%

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Lagoon Pond	36.208	22.418	-38.1%
West Arm (South End Basin)	5.762	3.377	-41.4%
Upper Lagoon Pond Stream	4.827	4.827	0.0%
System Total	46.797	30.622	-34.6%

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Lagoon Pond	22.418	7.156	26.650
West Arm (South End Basin)	3.377	0.921	8.717
Upper Lagoon Pond Stream	4.827	-	-
System Total	30.622	8.077	35.368

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change over background in Nantucket Sound (0.290 mg/L), for the Lagoon Pond system. The sentinel threshold station is shown in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Lagoon Pond head at dike	LGP-6	0.413	0.391	-17.6%
Lagoon Pond Head	LGP-4	0.385	0.365	-21.5%
Lagoon Pond upper Basin	**LGP-2**	**0.371**	**0.352**	**-22.8%**
Lagoon Pond mid Basin	LGP-8	0.338	0.326	-24.5%
Lagoon Pond lower Basin	LGP-9	0.328	0.319	-24.9%
West Arm (South End Basin)	LGP-10	0.378	0.357	-24.0%

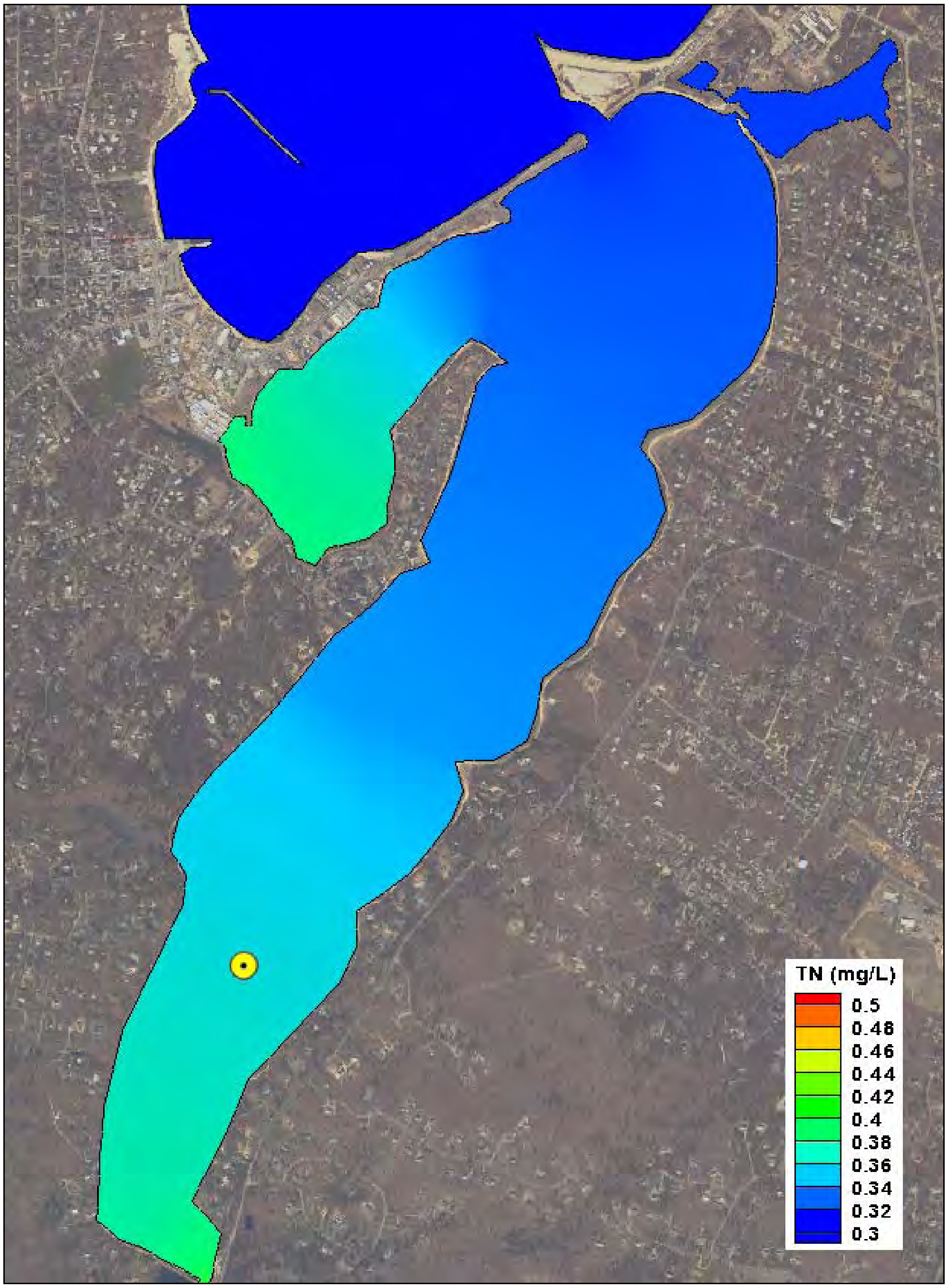


Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Lagoon Pond estuary, for threshold conditions. The sentinel threshold station is indicated by the yellow dot (0.35 mg/L at LGP-2 in the upper basin of Lagoon Pond).

IX. HYDRODYNAMIC AND WATER QUALITY MODEL SCENARIOS

Hydrodynamic and water quality model runs were performed to investigate quantitatively how flushing and TN concentrations would change in the Lagoon Pond system if culverts were placed under Beach Road, between the West Arm (South End Basin) and Vineyard Haven Harbor. Even though the tide data collected in the Pond (Section V.2.2) indicate that the system presently flushes very efficiently, with minimum tidal attenuation though the inlet, it is likely that water quality in the West Arm (South End Basin) could be improved by making a direct connection via culverts to lower TN concentration water in the Harbor and Nantucket Sound.

For this analysis, a total of six eight-foot-wide culverts were placed in the model at the locations indicated in Figure IX-1. The longest culverts are approximately 240 feet long. The number, size and placement of the culverts were not optimized, and issues related to other water quality factors, including coliform bacteria, were not investigated.

Figure IX-1. Location of six culverts (two each at A, B and C) placed in the hydrodynamic model of Lagoon Pond to investigate possible water quality improvements.

IX.1 HYDRODYNAMIC MODIFICATIONS TO THE BEACH ROAD CULVERT

Modifications were made to the model grid of the calibrated Lagoon Pond hydrodynamic model to include the six culverts. In order to directly compare the results of this model run to existing conditions, the culvert scenario was run with the same open boundary tide in Vineyard Haven Harbor.

The results of the hydrodynamic model run support the conclusions about system flushing efficiency that were made from the analysis of the measured tide data; The addition of the culverts does not increase the tide prism of Lagoon Pond, it only changes how water flooding and ebbing Lagoon Pond is distributed. An analysis of the modeled tidal prisms throughout the Lagoon Pond System indicates that with the addition of the culverts, 20% of the total tidal prism of the West Arm (South End Basin) would enter through the culverts. At present this tidal volume enters through the main inlet and through the lower reach of the east arm of Lagoon Pond. This may provide some improvement in nitrogen levels in the West End Basin to the extent that east arm water mixes with inflowing Vineyard Haven water and raises its total nitrogen level compared to water entering directly to West End Basin through the culverts. However, it does not appear that the effect would be large, although water quality modeling would need to be conducted to quantify the magnitude of potential improvement.

IX.2 TOWN WATERSHED LOADING SCENARIOS USING OPTIMIZED CULVERT

Using the RMA-2 hydrodynamic model output of the modeled culvert scenario, a TN model run was executed using the present conditions watershed loading (Table VI-2). The results of this run are presented in Table IX-1 and Figure IX-2.

These model results indicate that TN concentration improvements are possible with the addition of culverts through Beach Road. However, the improvements are confined to the West Arm (South End Basin), and do not help to reduce TN concentrations in the main basin of Lagoon Pond. TN concentration changes in the upper portions of the Pond were negligible, as expected. The largest decrease in TN concentrations occurred in the West Arm (South End Basin), where the modeled TN concentration decreased over 28% at station LGP-10. The TN concentration at the sentinel station LGP-2 remains essentially unchanged, which indicates that the addition of culverts under Beach Road is not a useful alternative for the threshold restoration goals set in Chapter VIII.

Table IX-1. Comparison of model average total N concentrations from present conditions and the modeled culvert scenario, with percent change over background in Nantucket Sound (0.290 mg/L), for the Lagoon Pond system. The sentinel threshold station is shown in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	Culvert Scenario (mg/L)	% change
Lagoon Pond head at dike	LGP-6	0.413	0.408	-4.4%
Lagoon Pond Head	LGP-4	0.385	0.382	-3.8%
Lagoon Pond upper Basin	**LGP-2**	**0.371**	**0.367**	**-4.5%**
Lagoon Pond mid Basin	LGP-8	0.338	0.335	-7.5%
Lagoon Pond lower Basin	LGP-9	0.328	0.325	-8.9%
West Arm (South End Basin)	LGP-10	0.378	0.353	-28.6%

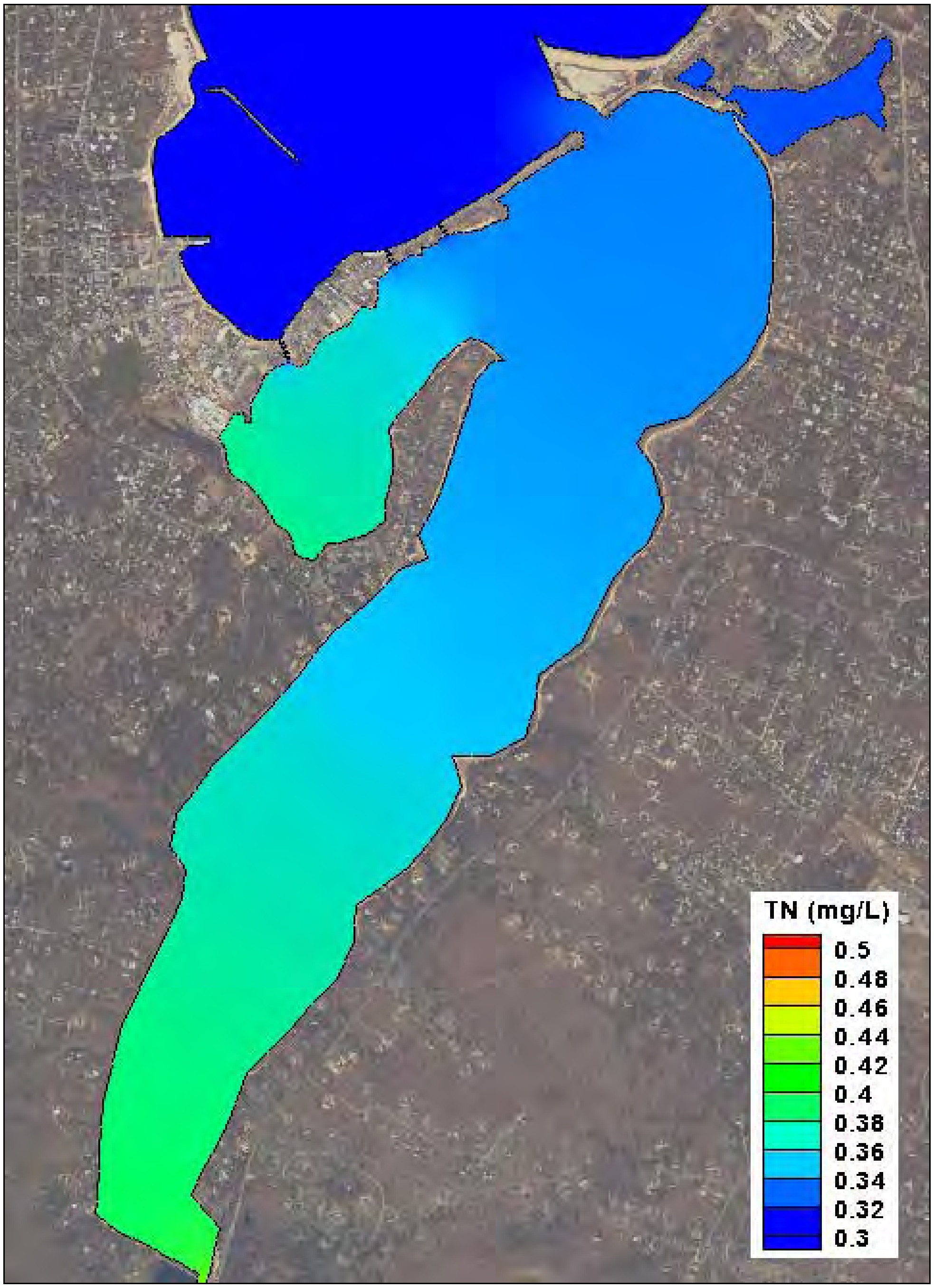


Figure IX-3. Contour plot of modeled total nitrogen concentrations (mg/L) in the Lagoon Pond estuary, for the modeled culvert scenario.

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