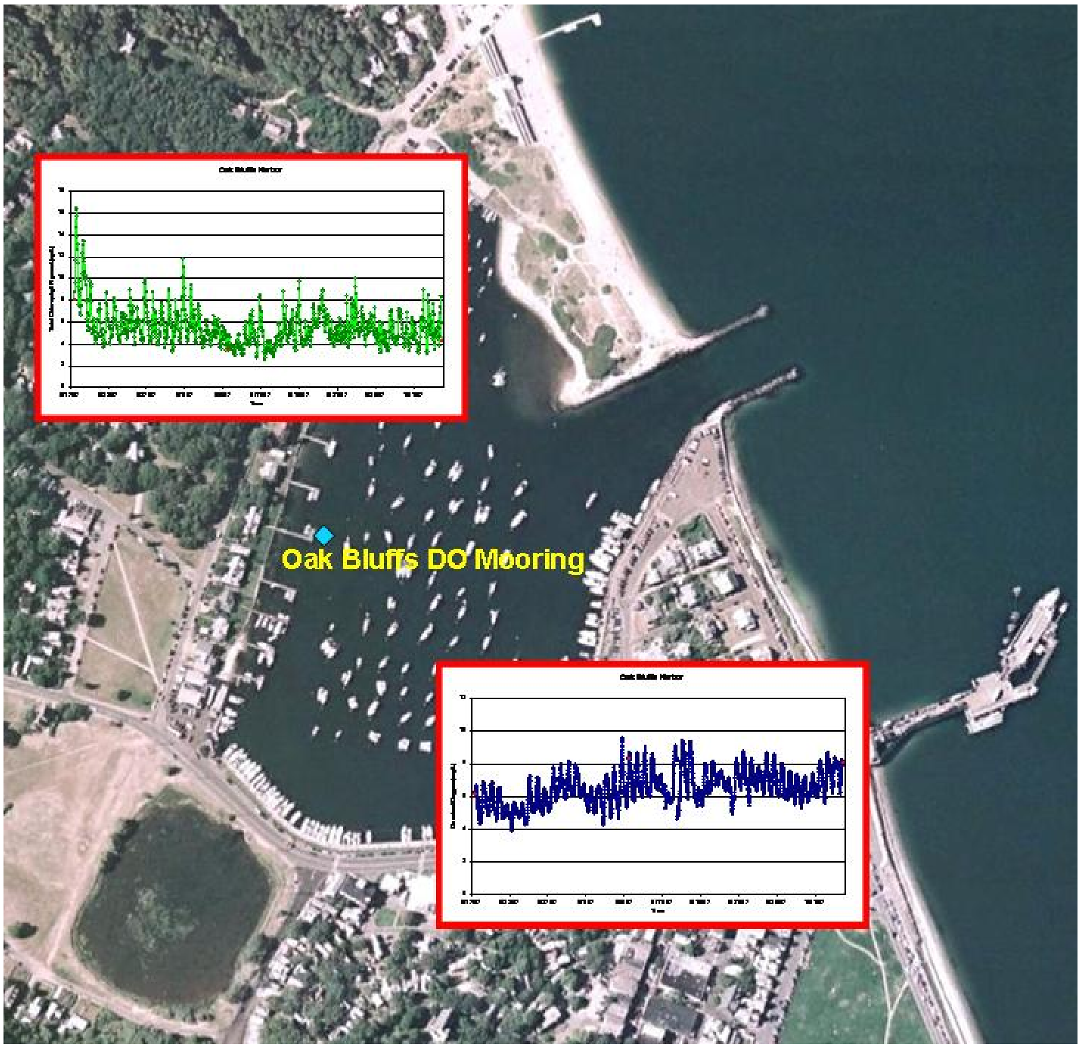
Massachusetts Estuaries Project

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



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

FINAL REPORT – May 2013

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Executive Summary

1. Background

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Oak Bluffs Harbor and Sunset Lake Embayment System, a coastal embayment situated entirely within the Town of Oak Bluffs, Massachusetts. Analyses of the Oak Bluffs Harbor / Sunset Lake Embayment System was performed to assist the Town of Oak Bluffs with on-going nitrogen management decisions associated with the current and future wastewater planning efforts of the Town, 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 (infauna). Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Town of Oak Bluffs resource planning and decision-making process. The primary products of this effort are: (1) a current quantitative assessment of the nutrient related health of the Oak Bluffs Harbor and Sunset Lake Embayment System, (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 Town) for the restoration of the overall 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 Oak Bluffs Harbor and Sunset Lake Embayment System within the Town of Oak Bluffs is at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater from the increasingly developed watershed to this coastal system. Eutrophication is a process that occurs naturally and gradually over a period of tens or hundreds of years. However, human-related (anthropogenic) sources of nitrogen may be introduced into ecosystems at an accelerated rate that cannot be easily absorbed, resulting in a phenomenon known as cultural eutrophication. In both marine and freshwater systems, cultural eutrophication results in degraded water quality, adverse impacts to ecosystems, and limits on the use of water resources.

The Town of Oak Bluffs has recognized the severity of the problem of eutrophication and the need for watershed nutrient management and is currently engaged in wastewater management at a variety of levels. For the Town of Oak Bluffs, this analysis of the Oak Bluffs Harbor and Sunset Lake Embayment System will need to be considered relative to the other analyses completed by the MEP for Lagoon Pond as well as Farm Pond and Sengekontacket Pond in order to plan out and implement a unified town-wide approach to nutrient management for Oak Bluffs. The Town with associated working groups (e.g. Shellfish Department) has 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 Town 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) and the Martha's Vineyard Commission (MVC) 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 Oak Bluffs Harbor and Sunset Lake 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 Coastal Systems Program within the University of Massachusetts-Dartmouth, School for Marine Science and Technology (see Section II). Evaluation of upland nitrogen loading was conducted by the MEP and data was provided by the Planning Departments in the Town of Oak Bluffs 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 Oak Bluffs Harbor and Sunset Lake Embayment System 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 Oak Bluffs Harbor / Sunset Lake 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 Oak Bluffs Harbor and Sunset Lake 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 the Vineyard/Nantucket Sound source waters were taken from water quality monitoring data offshore. Measurements of current salinity distributions throughout the estuarine waters of the Oak Bluffs Harbor 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 Oak Bluffs Harbor and Sunset Lake 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 station chosen for the Oak Bluffs Harbor and Sunset Lake Embayment 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 Oak Bluffs Harbor / Sunset Lake embayment system in the Town of Oak Bluffs. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. Hydrodynamic and water quality model runs were performed to investigate quantitatively how TN concentrations would change in the Oak Bluffs Harbor system if nitrogen loads to the estuary were reduced.

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 79% of the controllable watershed load to the Oak Bluffs Harbor and Sunset Lake 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 Oak Bluffs Harbor / Sunset Lake embayment system based upon available water quality monitoring data, historical information of eelgrass distribution, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure. At present, the Oak Bluffs Harbor system is not showing signs nitrogen enrichment and there is no nutrient related impairment of infaunal habitats (Section VII), indicating that nitrogen management of this system will be for protection rather than for restoration of an impaired system. The Oak Bluffs Harbor Embayment System is a man-made open water embayment significantly altered by human activity over the past approximately 100 years. Oak Bluffs Harbor was originally a coastal pond, Lake Anthony (sometimes also called Meadow Pond), until it was opened to tidal flows and the inlet stabilized in the 1800's to create a marine harbor. The harbor continues to be maintained by dredging, with the main basin dredged in 1971-1972 and dredging to remove shoaling in 2006.

All of the available information on eelgrass relative to the man-made and heavily altered Oak Bluffs Harbor System indicates that this embayment has not supported eelgrass over the past half century and likely has not supported eelgrass over the century that the system has been tidal. As eelgrass habitat could not be documented to exist, either historically or presently, within the Oak Bluffs Harbor Embayment System, the threshold analysis for this system is necessarily focused on restoration/protection of infaunal animal habitat.

Within the Oak Bluffs Harbor main basin there were moderate daily excursions in oxygen levels, generally ranging from air equilibration to 5 mg L^{-1} and very infrequently to 4 mg L^{-1}. Oxygen levels occasionally exceeded 8 mg L^{-1} and rarely exceeded 9 mg L^{-1}. These moderate oxygen levels are likely the result of the combined effects of low photosynthesis due to the low phytoplankton biomass and the relatively well flushed water in the Harbor. Chlorophyll levels generally remained between 4-10 ug L^{-1}, averaging only 6 ug L^{-1} and exceeded the 10 ug L^{-1} benchmark only 2% of the time. Chlorophyll-*a* levels over 10 ug L^{-1} have been used to indicate moderate nitrogen enrichment in embayments. The levels in Oak Bluffs Harbor are relatively low for enclosed temperate basins during summer. From the water quality data it would appear that the Oak Bluffs Harbor Embayment System is below its nitrogen assimilative capacity, the level of nitrogen enrichment a system can assimilate without habitat impairment.

Overall, the benthic infauna survey indicated that the main basin of Oak Bluffs Harbor is supporting a patchy distribution of high quality and impaired benthic habitat. Bottom surveys by SCUBA divers indicated areas with bay scallops and dense populations of quahogs (*Mercenaria)*, large numbers of fish and shrimp. While a detailed analysis of other factors that can also cause habitat impairment was not undertaken as part of this MEP analysis, there is evidence that disturbance of the bottom sedimentary habitat is likely playing a role in the main Harbor basin. The area of dredging activity conducted in May 2006 was confirmed through the Town of Oak Bluffs Shellfish Constable (personal communication, Mr. Dave Grunden). Dredging occurred ~ 5-months prior to the MEP infauna surveying activity and was limited to the area of the main navigational channel into the Harbor from the Harbormasters Office out the inlet channel. Dredging activity would not have affected areas of the 2006 MEP infaunal survey. More significant, however, appears to be disturbance of the sediments associated with the intense use of the Harbor as a marina and mooring area.

The above conclusion is supported by the higher quality infauna habitat observed within Sunset Lake. This small 3 acre basin, has higher tidally averaged nitrogen levels than the main Harbor basin (0.41 mg N L^{-1} versus 0.32 mg N L^{-1}), yet supports infaunal communities with 26 species and >500 individuals, with high diversity (3.8) and Evenness (0.8), but supports no boat related activities. The benthic animal communities in the basin of Sunset Lake are comparable to high quality environments, such as the Outer Basin of Quissett Harbor. Yet the main basin of Oak Bluffs Harbor, with its lower total nitrogen and Chlorophyll-*a* levels and generally good oxygen levels, has only low-moderate numbers of species and individuals forming a community of low - moderate diversity and Evenness. If the cause of the impaired benthic habitat in the main basin of Oak Bluffs Harbor were nitrogen enrichment then at the higher nitrogen levels observed in Sunset Lake the habitat should be worse, but it is generally better than the main Harbor basin.

Based upon integrating all of the metrics and supporting information (water quality parameters, heterogeneity of the benthic habitat quality and presence of high quality benthic habitat within Sunset Lake at significantly higher levels of nitrogen enrichment) it must be concluded that while the benthic animal habitat within the main Harbor basin is impaired, the impairment cannot be attributed to nitrogen enrichment. Instead, at this time it appears that the benthic habitat impairment is most likely the result of disturbance associated with an intensively used marine Harbor.

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 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 Oak Bluffs harbor and Sunset Lake Embayment system in the Town of Oak Bluffs were comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 79% of the controllable watershed nitrogen load to the embayment was from wastewater and the next largest load being from impervious surface run-off at 9% of the total controllable load.

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 the Oak Bluffs Harbor / Sunset Lake Embayment System.

The threshold nitrogen levels for the Oak Bluffs Harbor and Sunset Lake Embayment System were determined as follows:

Oak Bluffs Harbor and Sunset Lake Threshold Nitrogen Concentrations

- The sentinel station for the Oak Bluffs Harbor Embayment System was established within the mid basin of Sunset Lake and nitrogen threshold target developed to prevent nitrogen related degradation of benthic animal habitat throughout the system. As there was not a long-term water quality monitoring station within Sunset Lake, the water quality model was used to determine the present tidally averaged total nitrogen level under present loading conditions at mid-basin, in order to refine nitrogen threshold development (Section VI). Using this approach, the tidally averaged total nitrogen level at the sentinel station is presently 0.41 mg TN L^{-1}. This TN levels is comparable to other estuarine basins throughout the region that show similar water quality, organic enrichment and unimpaired benthic animal habitat. In numerous estuaries it has been previously determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat (e.g. Eel Pond, Parkers River, upper Bass River, upper Great Pond, upper Three Bays, Rands Harbor and Fiddlers Cove). However, it appears that Sunset Lake is presently near its threshold, so a threshold level of 0.45 mg TN L^{-1} is more appropriate to be protective of this nitrogen sensitive basin.

For protection of the Oak Bluffs Harbor and Sunset Lake 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 criteria of healthy infauna are also within an acceptable range. The goal is to achieve the nitrogen target at the sentinel location and maintain healthy infaunal habitat throughout the overall system. This goal should, however, be kept within the framework that the main basin of the harbor is a very active area that is subject to disturbance of benthic environments due to boating activity.

It is important to note that while the analysis of future nitrogen loading to the Oak Bluffs Harbor and Sunset Lake Embayment System does consider additional shifts in land-use from forest/grasslands to residential and commercial development, the MEP analysis does indicate that only modest 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. Overall, the whole of the Oak Bluffs Harbor and Sunset Lake Embayment System watershed is presently near build-out and when fully developed the total unattenuated nitrogen loading to the watershed will increase by only 22%. While future nitrogen loading to the system is limited, because existing nitrogen concentrations in the pond are only slightly lower than the threshold concentrations, 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 Oak Bluffs Harbor and Sunset Lake Embayment System is that protection will require that nitrogen loading to the harbor not exceed the present (2012) nitrogen inputs and management options designed to negate additional future nitrogen inputs.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Oak Bluff Harbor and Sunset Lake Embayment System, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. (mg/L)
SYSTEMS										
Oak Bluffs Harbor	0.477	0.800	4.307	0.433	5.540	0.430	10.132	16.102	0.27-0.38	--
Sunset Lake	0.148	0.398	7.036	--	7.704	0.063	-4.283	3.484	0.35-0.41	0.450
System Total	**0.625**	**1.198**	**11.343**	**0.433**	**13.244**	**0.493**	**5.849**	**19.586**	**0.27-0.41**	**0.450[8]**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings
[5] atmospheric deposition to embayment surface only
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 2001 – 2007 data, ranges show the upper to lower regions (highest-lowest) of an sub-embayment. individual yearly means and standard deviations in Table VI-1.
[8] Threshold for sentinel site located in Oak Bluffs Harbor at water quality station SUN-1.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Oak Bluff Harbor and Sunset Lake Embayment System, Town of Oak Bluffs, Massachusetts.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
SYSTEMS						
Oak Bluffs Harbor	5.540	6.386	0.430	11.258	18.074	-15.27%
Sunset Lake	7.704	10.123	0.063	-5.631	4.555	-31.40%
System Total	**13.244**	**16.509**	**0.493**	**5.6257**	**22.629**	**-24.65%**

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

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

First and foremost we would like to recognize and applaud the significant time and effort in data collection and discussion spent by members of the Martha's Vineyard Commission and the Town of Oak Bluffs Shellfish Department's Water Quality Monitoring Program. These individuals gave of their time to develop a consistent and sound baseline of nutrient related water quality for this system, which is necessary for the validation of the present analysis.

Staff from the Martha's Vineyard Commission and the Town of Oak Bluffs as well as volunteers have provided essential insights toward this effort. Of particular note has been the efforts of Mr. Dave Grunden (Oak Bluffs Shellfish Constable), Mr. Bill Wilcox (past MVC Water Resources Planner) and Ms. Sheri Caseau (present MVC Water Resources Planner), all of whom have spent countless hours mining and reviewing data and information with MEP Technical Team members in support of the MEP analysis of Oak Bluffs Harbor. Similarly, Chris Seidel, GIS Specialist from the MVC, provided significant support for the MEP land-use analysis, particularly analysis of parcel information and site-specific loading information (e.g. related to wastewater disposal). The efforts of the Oak Bluffs Water District (OBWD) for generously providing average water use information for properties within and near the Oak Bluffs Harbor watershed are also sincerely appreciated.

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

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I. INTRODUCTION

The Oak Bluffs Harbor and Sunset Lake Embayment System is a simple estuary located within the Town of Oak Bluffs on the island of Martha's Vineyard, Massachusetts. This estuary presently exchanges tidal waters with Vineyard/Nantucket Sound via a single large armored inlet through its eastern shore which supports a navigational channel (Figure I -1 and Figure I-2). Tidal flushing of this system has been highly altered over the past 150 years by storms and human alteration. Prior to the mid-1800's Oak Bluffs Harbor did not exist as a harbor but rather a coastal salt pond known as Lake Anthony (also sometimes called Meadow Pond). The ~30 acre Lake Anthony was separated from the Sound by the existing barrier beach. Sometime prior to 1858, the barrier beach was breached to connect Lake Anthony to Vineyard/Nantucket Sound and the main basin and tidal channel dredged to form an open water tidal basin for use as a marine harbor. Around the turn of the century, the harbor inlet was armored with jetties to create the present day inlet (Martha's Vineyard Commission, 2003). The smaller tidal basin (~4.5 acres) of Sunset Lake serves as a sub-embayment to Oak Bluffs Harbor, with nearly unrestricted tidal exchange from the main Harbor basin. Tidal exchange is via a box culvert under Lake Avenue.

Figure I-1. Location of the Oak Bluffs Harbor and Sunset Lake Embayment System, Island of Martha's Vineyard, Town of Oak Bluffs, Massachusetts. Oak Bluffs Harbor was historically a coastal salt pond, before (prior to 1858) the inlet was created through the barrier beach opening Lake Anthony to tidal flows from with Vineyard / Nantucket Sound and creating a marine harbor.

Figure I-2. Study region for the Massachusetts Estuaries Project analysis of the Oak Bluffs Harbor / Sunset Lake Embayment System. Tidal waters enter the Harbor from Vineyard Sound through the main harbor inlet. An existing culvert passing under Lake Avenue provides a hydraulic connection between Sunset Lake and Oak Bluffs Harbor. Freshwater enters from the watershed primarily through direct groundwater discharge as there are no significant surface water inflows to this system. The Oak Bluffs Harbor and Sunset Lake Embayment System is a highly man-altered system behind a very dynamic barrier beach where coastal processes are constantly depositing sands within the tidal inlet to the harbor.

Tidal exchange is essential to maintaining habitat quality of estuaries, as restrictions to tidal exchange increase the sensitivity of these systems to the negative effects of nitrogen loading. Nitrogen loading to the Oak Bluffs Harbor and Sunset Lake Embayment System watershed is primarily from residential and commercial development with little nitrogen stemming from the open space that comprises a portion of the lower and middle watershed area. Unlike the watersheds to most estuaries in southeastern Massachusetts, the watershed to Oak Bluffs Harbor and Sunset Lake does not contain any large freshwater ponds, streams or wetlands. Where these surface water systems exist in a watershed, they reduce nitrogen passing through during transport from up-gradient sources to down gradient estuarine waters. Effective management of the Oak Bluffs Harbor / Sunset Lake Embayment System will require consideration of all sources of nitrogen load relative to rates of tidal exchange with Vineyard/Nantucket Sound. As the entire watershed and estuarine waters of the Oak Bluffs Harbor and Sunset Lake Embayment System are contained within a single municipality, the Town of Oak Bluffs, this should streamline the development and implementation of a comprehensive nutrient management and restoration plan for the Harbor, since inter-municipal issues of load allocation and timing are absent.

The watershed to the Oak Bluffs Harbor Embayment System (Oak Bluffs Harbor + Sunset Lake) is completely sited within the Nantucket Moraine sediments consisting mainly of folded pre-Wisconsin clay, sand, gravel and glacial till overlain by Wisconsin drift (Woodworth and Wigglesworth 1934). These sediments were deposited as the ice sheets retreated at the end of the last glacial period. The late Wisconsinan Laurentide ice sheet reached its maximum extent and southernmost position about 20,000 years before present (BP), as indicated by the presence of terminal moraines on Martha's Vineyard and Nantucket and the southern limit of abundant gravel on the sea floor of Nantucket Sound and Vineyard Sound (Schlee and Pratt, 1970; Oldale, 1992; Uchupi et al., 1996). The lobate ice front was comprised of the Buzzards Bay lobe that deposited the moraine along the western part of Martha's Vineyard, the Cape Cod Bay lobe that deposited the moraines across eastern Martha's Vineyard and Nantucket, and the South Channel lobe that extended east toward Georges Bank (Oldale and Barlow, 1986; Oldale, 1992). During the retreat of the ice sheet, approximately 18,000 years BP, the Nantucket Moraine and the outwash plain that forms the central and southern portion of Martha's Vineyard were deposited. While the watershed was formed on the order of 18,000 years ago, the Oak Bluffs Harbor and Sunset Lake Embayment System is a much more recent development. Prior to its being dredged and armored to its present form, the former Lake Anthony was likely a coastal freshwater pond as sea level rose until <1,000 years ago. With rising sea level and in its former configuration it is nearly certain that this basin would begin to periodically receive salt water in overwash events or during temporary breaches during storms. With continued sea level rise the entry of salt water would become more common. As similar basins today, if it were not regularly opened, the system would cycle between salt and brackish conditions resulting in an unstable and generally impaired aquatic environment. This cycling ceased when the pond was "permanently" opened ~150 years ago and deepened, with continuing man-made alterations to form the present open-water embayment system.

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

Oak Bluffs Harbor is an artificially opened coastal salt pond with generally unrestricted tidal exchange with offshore waters, except for when the inlet accumulates sediments and needs to be dredged to maintain navigability. In the coastal landscape it functions as an open water lagoonal estuary, an enclosed tidal basin formed behind a barrier beach, similar to Farm Pond and Sengekontacket Pond to the south. The Oak Bluffs Harbor and Sunset Lake Embayment System watershed does not currently support any major freshwater ponds, wetlands or streams. Historically, Sunset Lake, which is currently separated from the Harbor by Lake Avenue, may have been the most up-gradient end of the Oak Bluffs Harbor system. However, a culvert connecting Sunset Lake to the harbor was emplaced under the roadway, which is presently maintaining nearly unrestricted tidal exchange with the main harbor basin. Sunset Lake is a sub-basin to the main harbor with little dilution of salinity (28 ppt) over harbor waters (30 ppt), even though much of the freshwater entering the system is through Sunset Lake. Its lack of surface water inflows and tributary basins and the large centrally located tidal inlet tends to reduce gradients in nutrient related habitat quality within the Oak Bluffs Harbor main basin.

The tidal inlet from Oak Bluffs Harbor to Vineyard Sound is through an active barrier beach, which has resulted in periodic natural closures and openings and human alterations to "maintain" tidal flows. Both sides of the inlet were armored in 1899 with rock jetties to stabilize the inlet for navigational purposes, however, sediment transport and the infilling of the inlet remains a constant challenge and periodic dredging is needed to sustain tidal flows. Maintenance of the tidal exchange to Oak Bluffs Harbor is one of the key management factors for this system, since its sensitivity to watershed nitrogen additions (e.g. eutrophication) is related to the rate of exchange with high quality Vineyard Sound waters.

The primary ecological threat to the Oak Bluffs Harbor and Sunset Lake Embayment System, as is the case for virtually all other estuaries in southeastern Massachusetts, is degradation resulting from nutrient over-enrichment, although as an intensively used harbor, discharges associated with boats and maintenance can be a concern. At present, the 10+ year long listing by the USEPA of Oak Bluffs Harbor as "impaired" relates to regulatory issues associated with marina activities and closures due to bacterial contamination. However, fecal coliform contamination does not generally result in ecological impacts, but is focused on public health concerns related with consumption of shellfish harvested from the Harbor and Sunset Lake basins. The primary impact of bacterial contamination is the closure of shellfish harvest areas, rather than the destruction of shellfish and other marine habitats. The seasonal shellfish closure of the Harbor and Lake is not due to on-going measurement of bacteria levels, but rather is an administrative closure based solely on the intensity of boating activity in case of illicit or accidental boat discharges. In contrast, increased loading of the critical eutrophying nutrient (nitrogen) to the Oak Bluffs Harbor / Sunset Lake Embayment System, results in both habitat impairment and loss of the resources themselves. Within the Oak Bluffs Harbor and Sunset Lake Embayment System watershed, nitrogen loading has been increasing as land-uses have changed over the past 60 years. The nitrogen loading to this system, like almost all embayments in southeastern Massachusetts and the Islands, results primarily from on-site disposal of wastewater and WWTF discharges, and to a lesser extent fertilizer use and stormwater flows. This is discussed in detail in Section IV.1.

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

As the primary stakeholder to the Oak Bluffs Harbor and Sunset Lake Embayment System, the Town of Oak Bluffs, in collaboration with the Martha’s Vineyard Commission (MVC), has been among the first communities to become concerned over perceived degradation of its coastal embayments. One key development for the management of this system was the inclusion of Oak Bluffs Harbor into the water quality monitoring program of Martha's Vineyard's estuaries and salt ponds conducted by the Martha's Vineyard Commission (Bill Wilcox, MVC Water Resources Planner). The initial results of the Water Quality Monitoring Program (2001-2007 with the exception of 2002) indicated that Oak Bluffs Harbor may be starting to show evidence of nitrogen enrichment related to periodically restricted tidal exchange and watershed nitrogen loading. As part of assessing this system, the Town of Oak Bluffs and the Martha’s Vineyard Commission (MVC) undertook participation in the Massachusetts Estuaries Project to complete ecological assessment and water quality modeling for the development of nutrient thresholds for defining the management of estuarine habitats within the Oak Bluffs Harbor and Sunset Lake Embayment System.

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

While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff and volunteers over many years, and most notably from members of the Martha’s Vineyard Commission and the Town of Oak Bluffs Shellfish Department. The modeling tools developed as part of this program provide the quantitative information necessary for the Town of Oak Bluffs to develop and evaluate the most cost effective nitrogen management alternatives to restore this valuable coastal resource which is currently being degraded by nitrogen overloading. It is important to note that the Oak Bluffs Harbor / Sunset Lake System and the associated watershed have been significantly altered by natural and human activities over the past ~150 years. The major alteration affecting the systems response to nitrogen loads is associated with the dynamic nature of the barrier beach system and alteration of tidal exchange due to inlet occlusion and attempts to manage tidal flows. These alterations subsequently affect the sensitivity of the Harbor to nitrogen loading from its surrounding watershed. Therefore, restoration of this system should focus on managing nitrogen related habitat quality through both the management of watershed nitrogen loading and maintaining tidal exchange at appropriate levels.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

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

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

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

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

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

The major MEP nitrogen management goals are to:

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

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

- requires site specific measurements within each watershed and embayment;
- uses realistic "best-estimates" of nitrogen loads from each land-use (as opposed to loads with built-in "safety factors" like Title 5 design loads);
- spatially distributes the watershed nitrogen loading to the embayment;
- accounts for nitrogen attenuation during transport to the embayment;

- includes a 2D or 3D embayment circulation model depending on embayment structure;
- accounts for basin structure, tidal variations, and dispersion within the embayment;
- includes nitrogen regenerated within the embayment;
- is validated by both independent hydrodynamic, nitrogen concentration, and ecological data;
- is calibrated and validated with field data prior to generation of “what if” scenarios.

The Linked Model has been applied for watershed nitrogen management in approximately 60 embayments throughout Southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach’s greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing “what if” scenarios for evaluating watershed nitrogen management options.

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

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

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

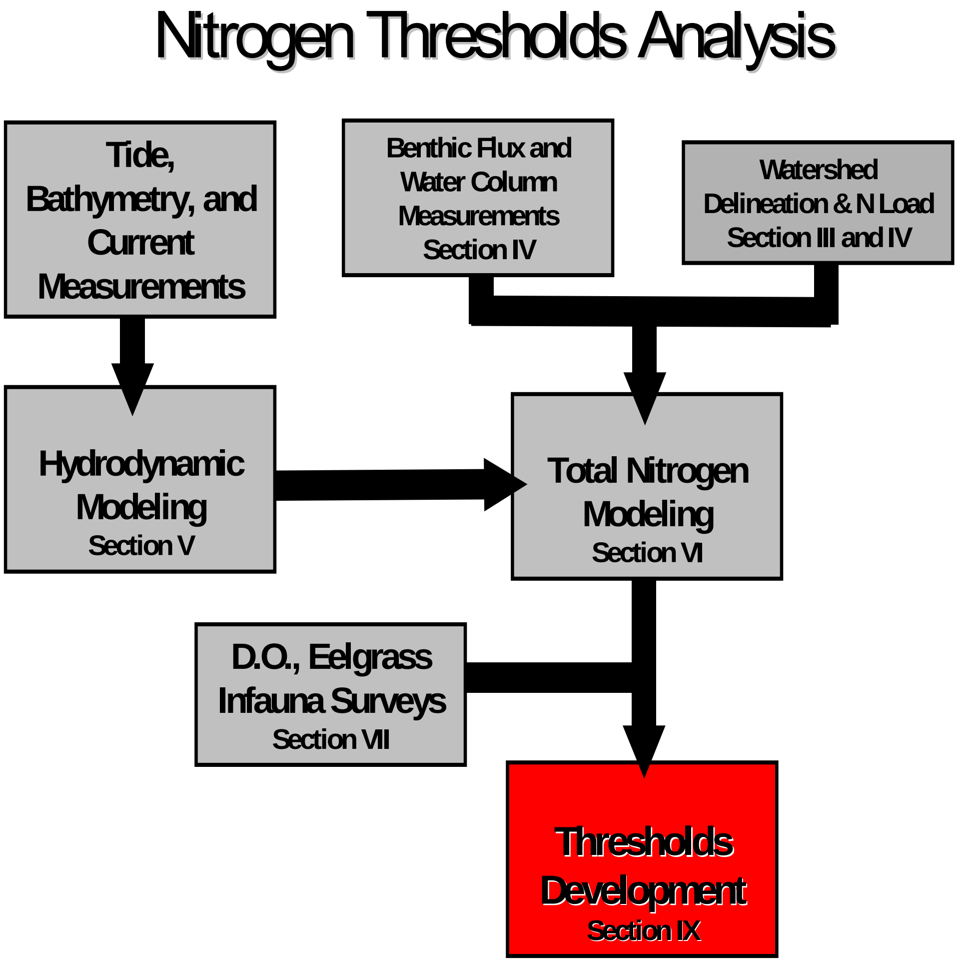


Figure I-3. Flow chart of key elements of the Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

I.2 NUTRIENT LOADING

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

Bluffs Harbor and Sunset Lake Embayment System follow this general pattern, with the Redfield Ratio (N/P = 7) indicating that the primary nutrient driving eutrophication in the system is nitrogen.

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

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

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

There has been concern, based primarily on preliminary studies, that the Oak Bluffs Harbor / Sunset Lake Embayment System is near or beyond its ability to assimilate additional nutrients without impacting the ecological health of the overall system. Nitrogen levels are elevated over offshore waters but there is little evidence of nitrogen related impairment, although benthic habitat may be under stress. A nitrogen gradient has been observed within the Oak Bluffs Harbor and Sunset Lake Embayment System showing lowest nitrogen and chlorophyll a levels nearest the tidal inlet and highest levels associated within the main harbor basin and Sunset Lake. As such, nitrogen management of the Oak Bluffs Harbor and Sunset Lake Embayment System is aimed at protection or possibly restoration of nitrogen related water quality for management of benthic animal habitat. There is no record of a historic or present day eelgrass resource within the tidal reaches of either the main basin of Oak Bluffs Harbor or Sunset Lake.

In general, nutrient over-fertilization is termed “eutrophication” and in certain instances can occur naturally over long periods of time. When the nutrient loading is rapid and primarily from human activities leading to changes in a coastal watershed, nutrient enrichment of coastal waters is termed “cultural eutrophication”. Although the influence of human-induced changes has increased nitrogen loading to the systems of Martha’s Vineyard, it was not clear prior to the MEP assessment if it was contributing to impairment of ecological health within the Oak Bluffs Harbor and Sunset Lake Embayment System, as the Harbor is sensitive to nitrogen inputs and more so, because of periodic sedimentation and potentially reduced flows through its tidal inlet. As part of future protection/restoration efforts for Oak Bluffs Harbor and Sunset Lake, it is important to understand that nitrogen management will restore habitat health only to the extent that it is the primary driver to any impairments. Similarly, depending upon the approaches employed, nitrogen management may not eliminate the periodic bacterial contamination of harbor and lake waters.

I.3 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” (e.g. watershed derived and offshore nutrient inputs) for water quality modeling of the Oak Bluffs Harbor and Sunset Lake 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 Oak Bluffs Harbor and Sunset Lake Embayment System. Given the depth of the basins and measurements of water column structure showing a generally well vertically mixed water column, a two-dimensional depth-averaged hydrodynamic model was developed based upon the configuration and tidal flows within the main basin of the harbor and Sunset Lake. Once the hydrodynamic properties of each component of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon MEP refined (working with the USGS and MVC) watershed delineations originally developed by Earth Tech. Almost all nitrogen entering the Oak Bluffs Harbor and Sunset Lake Embayment System is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Oak Bluffs Harbor waters were collected by the Town of Oak Bluffs/MVC Water Quality Monitoring Program (a coordinated effort between the Towns of Oak

Bluffs, the Martha's Vineyard Commission and the Coastal Systems Program at SMAST). Salinity and total nitrogen in inflowing Vineyard Sound waters were from the Nantucket Sound Monitoring Consortium surveys (2006-08) overseen by the Coastal Systems Program at SMAST. Measurements of nitrogen and salinity distributions throughout estuarine waters of the system (2001-2007) were used to calibrate and validate the water quality model (under existing loading conditions). The tidal flushing conditions for this analysis were based on a single inlet configuration, as existed prior to October 2009. The effect of different inlet configurations was evaluated as "scenario runs" using the calibrated and validated models.

I.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Oak Bluffs Harbor and Sunset Lake Embayment System for the Town of Oak Bluffs. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. Nitrogen loads from the watershed (by sub-watershed) surrounding the estuary were derived from the Martha's Vineyard Commission land-use database. In addition, nitrogen input parameters to the water quality model are described (Section IV). Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Results of hydrodynamic modeling of evaluation of tidal exchange to determine residence times, flushing characteristics and whether or not the system inlet is restricted is presented in Section V. Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities). Site specific nitrogen and salinity levels within the estuary and in inflowing waters were used to validate the water quality model, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of the component sub-embayments was performed that included a review of existing water quality information and the results of a benthic analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of the Pond in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration of the Pond. This latter assessment represents only one of many solutions and is produced to assist the Towns in developing a variety of alternative nitrogen management options for this system. The results of the nitrogen modeling for each scenario have been presented in Section VIII.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

In most marine and estuarine systems, including the Oak Bluffs Harbor and Sunset Lake Embayment System, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. As a result, there has been significant effort to develop tools for predicting how modification of watershed nitrogen loads and changes in tidal flushing quantitatively cause changes in the concentrations of water column nitrogen in the receiving estuary. Further development of these approaches generated specific guidelines as to what is to be considered acceptable water column nitrogen concentrations to achieve desired water quality goals (e.g., see Cape Cod Commission 1991, 1998; Howes et al. 2002).

These tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. In contrast, some approaches can be tailored for each individual estuary of interest, but require large amounts of site-specific information and therefore are not generally applied. The present Massachusetts Estuaries Project (MEP) effort uses one such site-specific approach. The assessment focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species within individual estuaries. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for the specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Oak Bluffs Harbor and Sunset Lake Embayment 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.

As the primary stakeholder to the Oak Bluffs Harbor and Sunset Lake Embayment System, the Town of Oak Bluffs, in collaboration with the Martha’s Vineyard Commission (MVC), has been among the first communities to become concerned over perceived degradation of its coastal embayments. As such, a comprehensive water quality monitoring program was initiated in 2001 for Oak Bluffs Harbor (inclusive on Sunset Lake) in order to establish the existing water quality conditions in the harbor system and gauge any habitat impairment. Additionally, a number of studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Oak Bluffs Harbor and Sunset Lake Embayment System over the past decade which helped to inform the MEP process.

Directly supporting the present Massachusetts Estuaries Project effort to develop a nitrogen threshold for Oak Bluffs Harbor are three key investigations which relate directly to assessing nutrient related water quality. These studies provided quantitative information regarding specific water column parameters over multiple summers (including nitrogen), initial estimates of nutrient loading to the harbor from the watershed and quantitative analysis of inlet dredging that has direct effect on circulation and flushing of the harbor. These studies are summarized below.

Nutrient Loading to Lake Anthony and Sunset Lake (MVC, 2003): In 2003 the Martha's Vineyard Commission completed a nutrient loading analysis of Lake Anthony (aka. Oak Bluffs Harbor) and Sunset Lake. The project period was 2001 through 2003 and data used in the nutrient loading analysis was collected in 2001. The report was completed for the Massachusetts Executive Office of Environmental Affairs (Massachusetts Watershed Initiative and the Massachusetts Department of Environmental Protection (Bureau of Resource Protection). This initial nutrient loading analysis was based on a watershed delineation defined using Topographic contours and groundwater contours (Whitman & Howard, Inc., 1994) where the "tail" of the uppermost part of the watershed was mapped using watershed boundaries for Lagoon Pond and Farm Pond, as previously mapped by the Martha's Vineyard Commission. For the flat areas of the densely populated portions of the watershed, information regarding stormwater drainage was used to calculate the volume of water reaching the Harbor. Ultimately, a watershed area was calculated using ARCGIS tools and a recharge value of 22.2 inches from 45.82 inches of rainfall was used to calculate the volume of recharge and freshwater discharge to the estuary. The groundwater flow was combined with a land use analysis of the watershed to produce an initial estimate of nutrient loading to Sunset Lake and the main basin of Oak Bluffs Harbor. The nutrient loading estimate was combined with a basic characterization of circulation in the Harbor (mainly residence time) and water quality measurement from the summer of 2001 to calculate a nitrogen loading limit for Lake Anthony (Oak Bluffs Harbor) based upon the Buzzards Bay Project (BBP) Approach (Costa et al. 1999). The loading limit determined in this initial nutrient loading study for this system was 2,800 kilograms per year compared to the estimated nitrogen load reaching the Harbor in 2001 of 12,818 kilograms/yr. The results suggested that a 78% reduction in existing watershed load might been needed for Harbor management. While this study was forward looking at the time, the underlying BBP model available at the time could not be calibrated or validated and did not assess the habitats within the estuary itself. Therefore, while the effort was thoughtful and well executed by the authors, the model was not sufficiently robust to accurately represent the Oak Bluffs Harbor System. Similar results have been observed for other estuaries (Howes et al. 2002). It should be noted that while the land-use analysis itself was of high quality, the nitrogen loading result was overestimated as a result of using nitrogen source strengths for commercial and residential septic systems and fertilizers from the BBP Approach. One significant difference in the present analysis compared to the previous approach was that actual water use data for the watershed was available for the MEP work, which was not available to the authors, who were required to use assumed rates. However, the major difference in outcomes results from the fact that the BBP model does take into account the internal hydrodynamics of an embayment, while the MEP approach uses a fully parameterized numerical modeling approach tailored to the specific embayment under analysis. None-the-less the 2003 report did provide valuable information on land-use and contained quantitative water quality data that benefited the present MEP effort (dissolved oxygen, chlorophyll, nitrogen forms and orthophosphate). This later data set and the momentum generated by this initial work was continued by those involved in the 2003 study which ultimately resulted in the present assessment. In working with the Martha's Vineyard Commission on the refinement of the watershed delineation and the land use analysis, the MEP is complementing the earlier nutrient loading limit by factoring data sets that were not previously available in 2003.

Oak Bluffs Harbor and Sunset Lake Embayment System Nutrient Related Water Quality Monitoring: The Martha's Vineyard Commission has worked with Martha's Vineyard towns to collaboratively monitor the nutrient related water quality (as opposed to bacteria) of the estuaries across the island. Oak Bluffs Harbor is one of those systems. Summertime monitoring of the water quality in Oak Bluffs Harbor began in 2001 and continued at a high level through 2007. This effort gained important support from the MassDEP 604(b) grant program in 2003 for its continuation. Intensive water quality sampling of the Oak Bluffs Harbor Embayment was completed by the Coastal Systems Program (SMAST) in 2004, 2005, 2006 and 2007 in collaboration with the MVC. In general, four summer sampling events were completed for each of the stations in Oak Bluffs Harbor for the period 2001-2007 (Figure II-1). In 2001-2004, the sampling program achieved 6, 4, 4 and 5 sampling rounds respectively. In 2005, 2006 and 2007, five stations were sampled with 5, 6, and 5 rounds of sampling being completed, respectively. The monitoring undertaken was a collaborative effort with the MVC (Bill Wilcox) coordinating the field effort in the first few years and chemical assays being completed by the SMAST Coastal Systems Analytical Facility throughout. For summers 2004-2007, the Coastal Systems Program completed both the sample collection and the chemical assays. The Coastal Systems Analytical Facility is located in the School for Marine Science and Technology UMASS-Dartmouth, 706 S. Rodney French Blvd, New Bedford, MA, and the laboratory Points of Contact are Sara Sampieri 508-910-6325 (ssampieri@umassd.edu) or Mike Bartlett (mbartlett@umassd.edu). Use of the SMAST Analytical Facility ensured sufficient sensitivity and accuracy of the analytical protocols and that proper QA/QC procedures were followed to allow incorporation of the data into the MEP analysis. The focus of the Oak Bluffs Harbor effort has been to gather site-specific data on the current nitrogen related water quality throughout its estuarine reach to support assessments of habitat health. This baseline water quality data are a prerequisite to entry into the MEP. Implementation of the MEP's Linked Watershed-Embayment Approach necessarily incorporates the quantitative water column nitrogen data (2001-2007) gathered by the Monitoring Program and watershed and embayment data collected by MEP staff.

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

- Designated Shellfish Growing Area – MassDMF (Figure II-2)
- Shellfish Suitability Areas – MassDMF (Figure II-3)

- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-4)

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

Figure II-1. Town of Oak Bluffs/MV Commission Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the Town of Oak Bluffs, MV Commission and SMAST staff during summers 2001-2007.

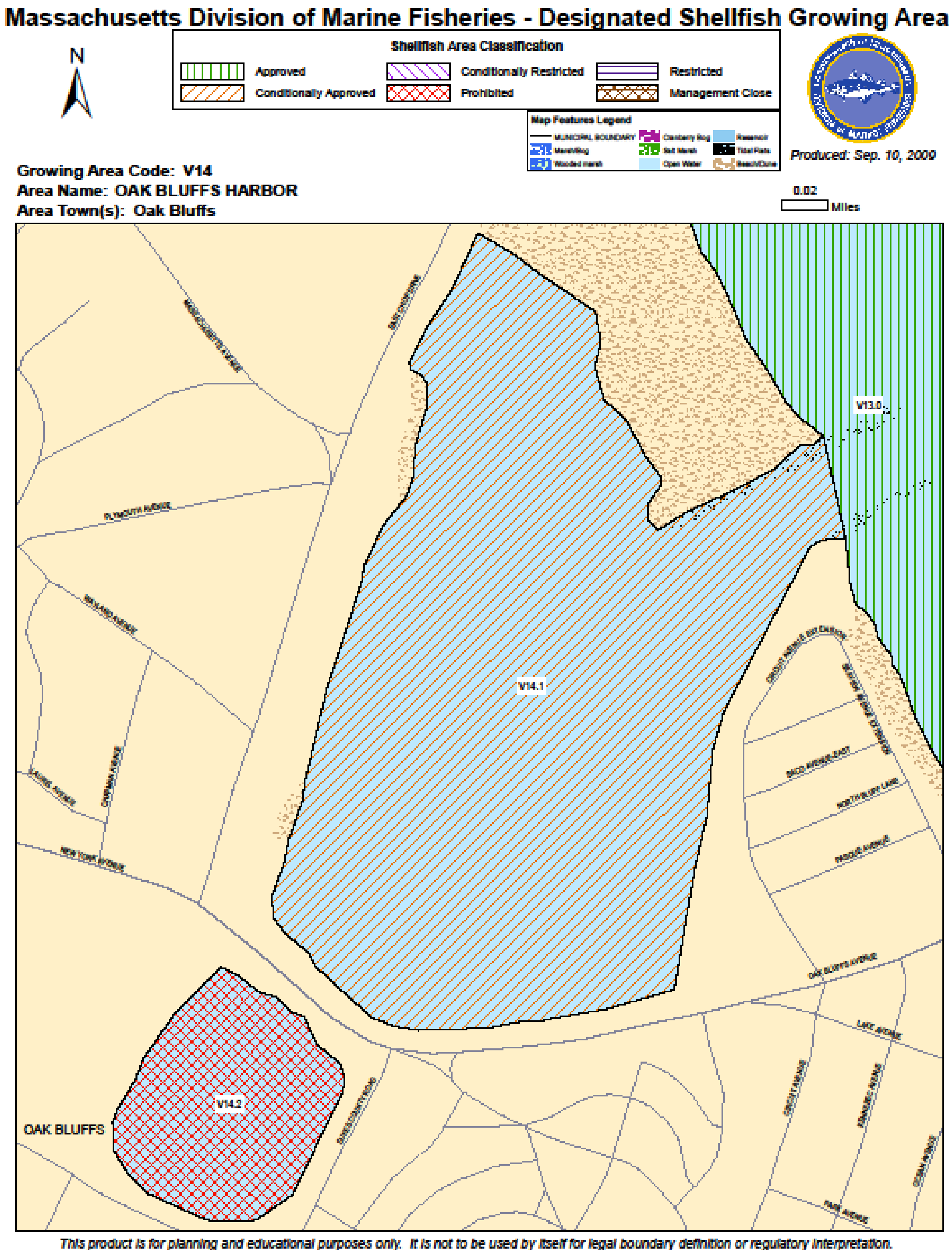


Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas. The seasonal closure of the main basin of the harbor relates to its summertime intensive use as a marine harbor and mooring area.

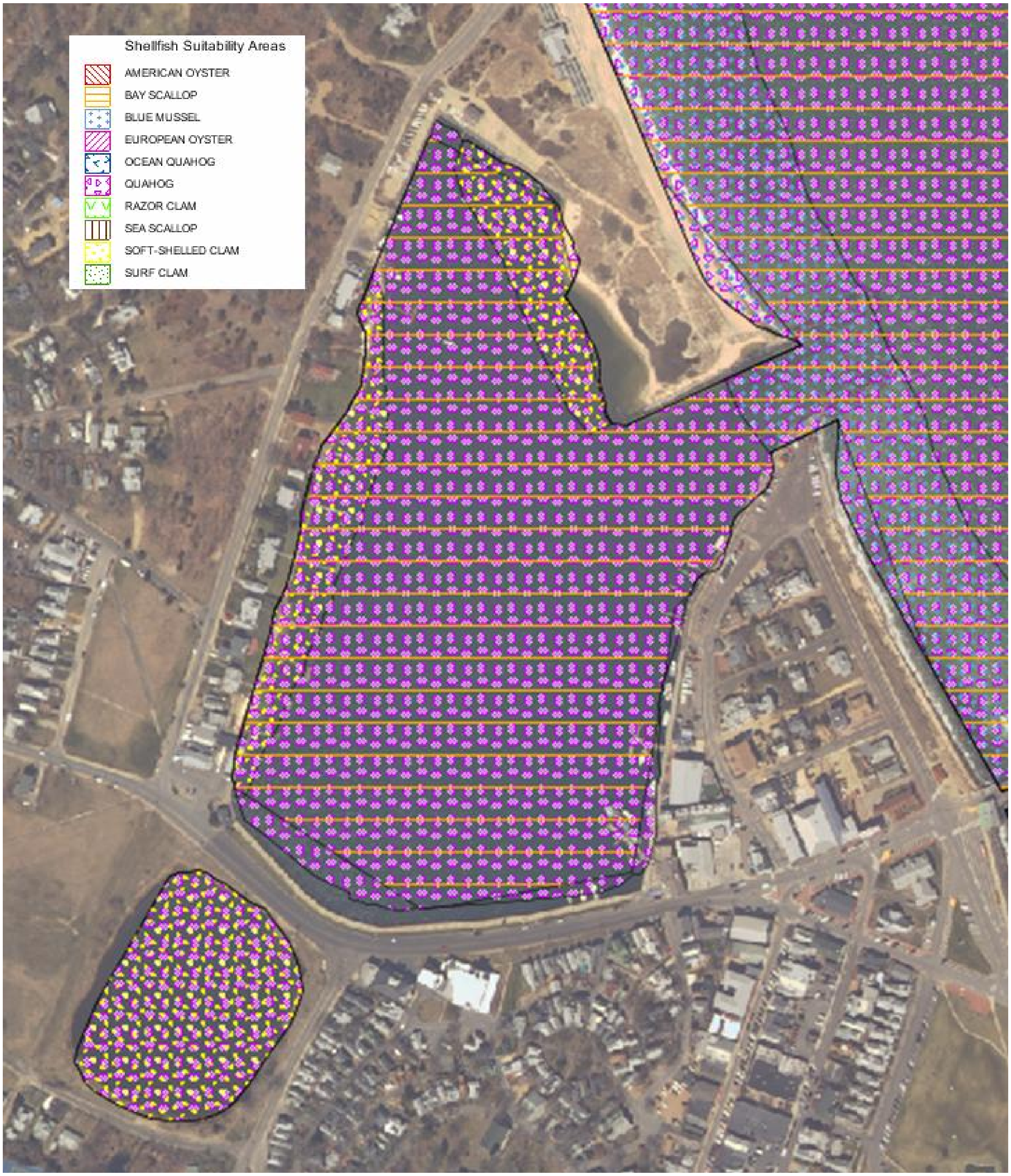


Figure II-3. Location of shellfish suitability areas (areas of habitat where different species of shellfish should be sustainable) within the Oak Bluffs Harbor and Sunset Lake Embayment System as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean that the shellfish species is "present".

Figure II-4. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Oak Bluffs Harbor and Sunset Lake Embayment System 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 and was formed by post-glacial processes (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. 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 streams 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). Delaney (1980) and subsequent characterizations have indicated that these characteristics also apply to the eastern moraine.

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 Oak Bluffs Harbor and Sunset Lake Embayment System watershed, all freshwater watershed inputs to the estuary are via groundwater as there are no streams flowing into this estuarine system.

The Oak Bluffs Harbor and Sunset Lake Embayment System and its watershed are mostly located within the eastern moraine of Martha's Vineyard. The watersheds utilized in the MEP assessment are largely based on delineations created and used by the Martha's Vineyard Commission (MVC). The groundwater system in the eastern moraine has generally been characterized as permeable as the outwash plain and the 1977 United States Geological Survey (USGS) regional water table map shows groundwater flow lines from the western moraine toward the eastern coast that seem uninfluenced by the moraine (Delaney, 1980). In 1991, the USGS developed another regional water table map, which generally showed the same water table contours (Masterson and Barlow, 1996). Masterson and Barlow used the 1991 water table readings as guidance for construction of a regional two-dimensional, finite-difference groundwater flow model that could be used to calculate drawdowns in groundwater levels due to pumping of public water supply wells, but could not be calibrated against actual water level readings. These characterizations of the hydrogeology, including the installation of numerous long-term monitoring wells, over the last few decades have provided the basis for subsequent activities, including the delineation and refinement of estuary watersheds. In 1994, Whitman and Howard produced a groundwater model with a domain that covered the Martha's Vineyard eastern moraine and the outwash plain; this model was based on the publicly available USGS

MODFLOW three-dimensional, finite difference groundwater model code. In 1999, Earth Tech updated the 1994 Whitman and Howard regional model and used an associated model to delineate watersheds. MVC used the model results and the groundwater contours to delineate a watershed to Oak Bluffs Harbor (Taylor, 2003). Regional watersheds were adopted by the MVC and are used in the MVC's guidance to the towns of Martha's Vineyard and for the regulatory review of Developments of Regional Impact. MEP staff worked with Bill Wilcox and other MVC staff to jointly re-review and refine the delineations of the Oak Bluffs Harbor and Sunset Lake Embayment System watershed and subwatersheds, including the sub-watershed to Sunset Lake.

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 OAK BLUFFS HARBOR AND SUNSET LAKE EMBAYMENT SYSTEM AND CONTRIBUTORY AREAS

The Oak Bluffs Harbor and Sunset Lake Embayment System watershed and sub-watershed delineations are based largely on previous historic delineations including reviews and refinements of the regional groundwater models and consultation among MEP partners and staff. 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 available refinements necessary to complete the Oak Bluffs Harbor and Sunset Lake Embayment System watershed delineation.

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

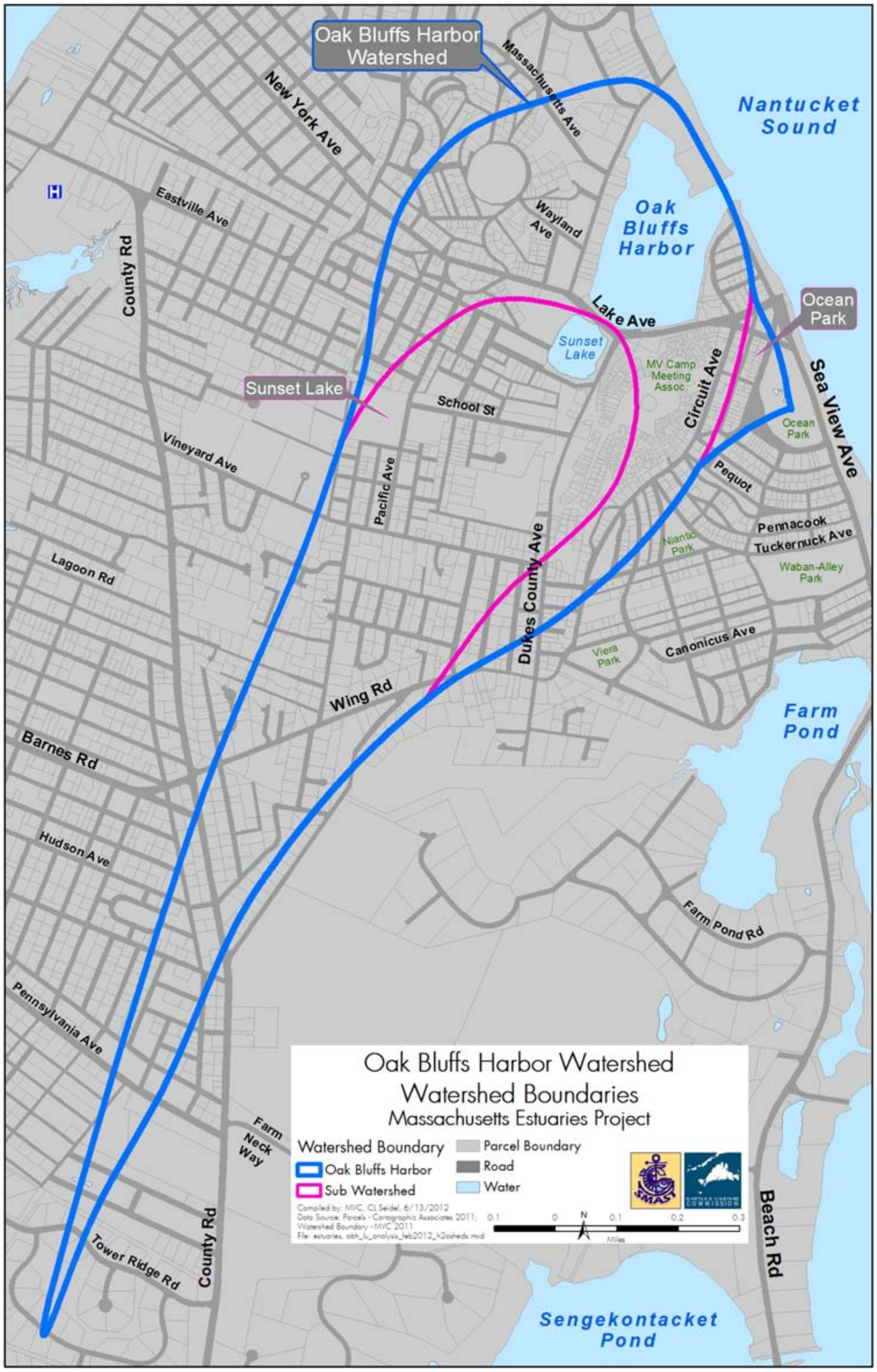


Figure III-1. Watershed and sub-watershed delineations for the Oak Bluffs Harbor and Sunset Lake Embayment System. Sub-watersheds to embayments are based upon watershed features and functional estuarine sub-units in the water quality model (see section VI).

MEP staff utilized the Oak Bluffs Harbor and Sunset Lake Embayment System watershed to develop daily discharge volumes for the two sub-watersheds as calculated from the watershed areas and an island-specific recharge rate; the Ocean Park subwatershed is technically part of the subwatershed to the main portion of the harbor, but is separately delineated. In order to develop the groundwater discharge volumes, MEP staff determined an annual 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 average 44.5 in/yr of precipitation on the Cape. Precipitation data collected by the National Weather Service at an Edgartown measuring station since 1947 has an annual average over the last 20 years of 46.9 inches (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 Oak Bluffs Harbor and Sunset Lake Embayment System and its various subwatersheds (Table III-1). The subwatershed discharge volumes were used to assist in the salinity calibration of the estuarine water quality model. The overall estimated groundwater flow into Oak Bluffs Harbor from the MEP delineated watershed is 3,192 m3/d.

Table III-1. Daily groundwater discharge from each of the sub-watersheds to the Oak Bluffs Harbor and Sunset Lake Embayment System.

Watershed	Watershed #	Watershed Area (acres)	Discharge	
			m^3/day	ft^3/day
Oak Bluffs Harbor Main	1	141	1,140	40,264
Ocean Park OBH	2	10	183	6,457
Sunset Lake	3	231	1,869	65,989
TOTAL		382	3,192	112,709

notes:

a. Discharge rates are based on 28.7 inches per year of recharge.
b. Ocean Park discharge flows include 105 m3/d from the Oak Bluffs WWTF.

The area for the MEP watershed delineation is similar to previous delineations. The MVC delineation completed for Taylor (2003) has an area of 402 acres including the surface areas of the estuary (Figure III-2). The comparable measurement of the MEP watershed is 416 acres including 10 acres for the Ocean Park subwatershed, which was not included in the 2003 watershed delineation. While there are some subtle differences in spatial coverage, the MEP watershed is only 3% larger than the earlier version, due almost entirely to the inclusion of the more recent analysis of the Ocean Park watershed (excluding Ocean Park sub-watershed, the difference is <1%). Given the incorporation of updates to the groundwater model and groundwater measurements at Ocean Park, MEP Technical Team staff are confident that the delineation in Figure III-1 is accurate and provides an appropriate basis for completion of the linked watershed-embayment model for Oak Bluffs Harbor and Sunset Lake.

Review of watershed delineations for the Oak Bluffs Harbor and Sunset Lake Embayment System 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 assessments 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 specific aquatic systems, such as the Oak Bluffs Harbor and Sunset Lake Embayment System (Section V.1).

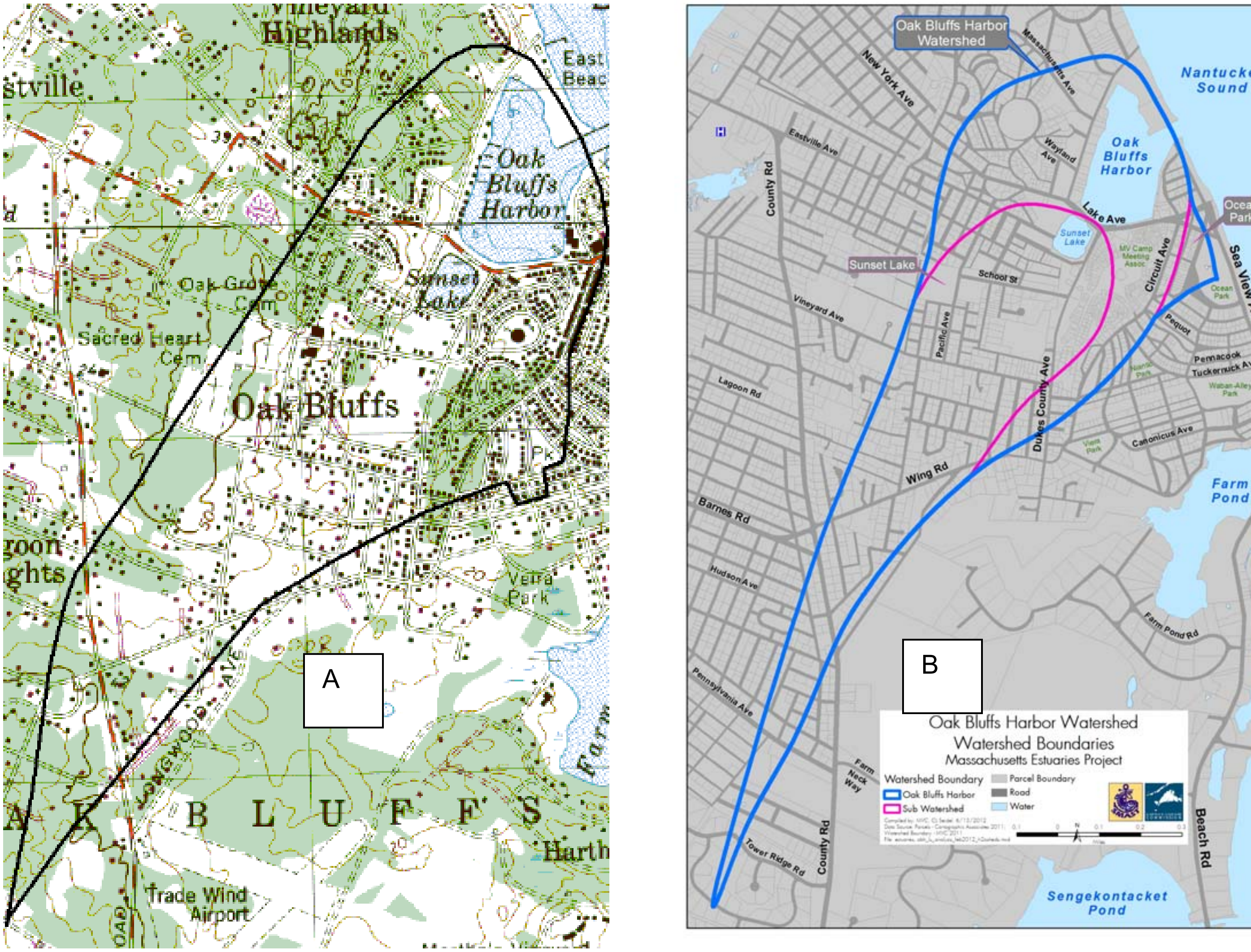


Figure III-2. Comparison of current MEP watershed delineation with historic Oak Bluffs Harbor watershed delineation. (A) shows delineation completed by Martha's Vineyard Commission (excerpted from Figure 3 in Taylor, 2003), while (B) shows the current MEP delineation. The MEP watershed delineation, which reflects subsequent data collection, is 3% larger than the 1989 delineation largely based on the inclusion of the Ocean Park subwatershed. Note that although the areas are very similar, there are some subtle changes in the spatial coverage.

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

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

Management of nutrient related water quality and habitat health in coastal waters requires determination of the amount of nitrogen transported by freshwaters (surface water flow, groundwater flow) from the surrounding watershed to the receiving embayment of interest. In southeastern Massachusetts, the nutrient of management concern for estuarine systems is nitrogen and this is true for the Oak Bluffs Harbor and Sunset Lake Embayment System. Determination of watershed nitrogen inputs to these embayment systems requires the (a) identification and quantification of the nutrient sources and their loading rates to the land or aquifer, (b) confirmation that a groundwater transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes. This latter natural attenuation process results from biological processes that naturally occur within ecosystems. Failure to account for attenuation of nitrogen during transport results in an over-estimate of nitrogen inputs to an estuary and an underestimate of the sensitivity of a system to new inputs (or removals). In addition to the nitrogen transport from land to sea, the amount of direct atmospheric deposition on each embayment surface must be determined as well as the amount of nitrogen recycling within the embayment, specifically nitrogen regeneration from sediments. Sediment nitrogen recycling results primarily from the settling and decay of phytoplankton and macroalgae (and eelgrass when present). During decay, organic nitrogen is transformed to inorganic forms, which may be released to the overlying waters or lost to denitrification within the sediments. Burial of nitrogen is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source of nitrogen to embayment waters or in some cases a sink for nitrogen reaching the bottom. Failure to include 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 coordinated the development of the watershed nitrogen loading for the Oak Bluffs Harbor and Sunset Lake Embayment System with Martha's Vineyard Commission (MVC) staff. This effort led to the development of nitrogen-loading rates (Section IV.1) to the Oak Bluffs Harbor watershed (Section III). The Oak Bluffs Harbor watershed is divided into three sub-watersheds; one to the main portion of Oak Bluffs Harbor, one to Sunset Lake and a third created by the discharge of treated wastewater from the Oak Bluffs Wastewater Treatment Facility at Ocean Park (see Section III). The Ocean Park sub-watershed is a portion of the Oak Bluffs Harbor Main sub-watershed, but has been delineated separately to better address its relationship to the groundwater mounding at Ocean Park.

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other in-depth studies is applied to other portions. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon sub-watershed-specific land uses and pre-determined nitrogen loading rates. For the Oak Bluffs Harbor and Sunset Lake Embayment System, the model used MVC-supplied town land-use data 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). Determination of the nitrogen loads required obtaining watershed specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the “potential” or unattenuated nitrogen load to each receiving embayment, since attenuation during transport 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. However, the watershed to Oak Bluffs Harbor and Sunset Lake Embayment System contains only 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 (0-5%) overestimated given the distribution of nitrogen sources and these features within the watershed. Based upon these considerations, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the three 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 Oak Bluffs Harbor and Sunset Lake Embayment System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Martha’s Vineyard Commission (MVC) staff, with the guidance of Estuaries Project staff, combined Town of Oak Bluffs digital parcel and tax assessor’s data from the MVC Geographic Information Systems Department. Digital parcels boundaries are from 2011 and land use/assessor’s data are from 2012. These land use databases contain traditional information regarding land use classifications (MADOR, 2009) plus additional information developed by the MVC.

Figure IV-1 shows the land uses within the watershed to the Oak Bluffs Harbor and Sunset Lake Embayment System. Land uses in the study area are grouped into eight land use categories: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) open space, 6) undeveloped, 7) public service/government, including road rights-of-way, and 8) unclassified. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2008). “Public service” in the MADOR system is tax-exempt properties, including lands owned by government (*e.g.*, wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges.

In the overall Oak Bluffs Harbor and Sunset Lake Embayment System watershed, the predominant land use based on area is residential properties, which account for 48% of the overall watershed area, with public service properties (government owned lands, roads, and rights-of-way) accounting for the second highest percentage of the watershed area (34%) (Figure IV-2). Residential properties are the majority of land area (54%) in the Sunset Lake sub-watershed, while public service properties are the majority of the land area (66%) in the Ocean Park sub-watershed. In the Oak Bluffs Harbor sub-watershed, residential and public service properties are approximately the same proportion of the sub-watershed area (40% and 38%, respectively). Undeveloped properties are 11% of the overall system watershed.

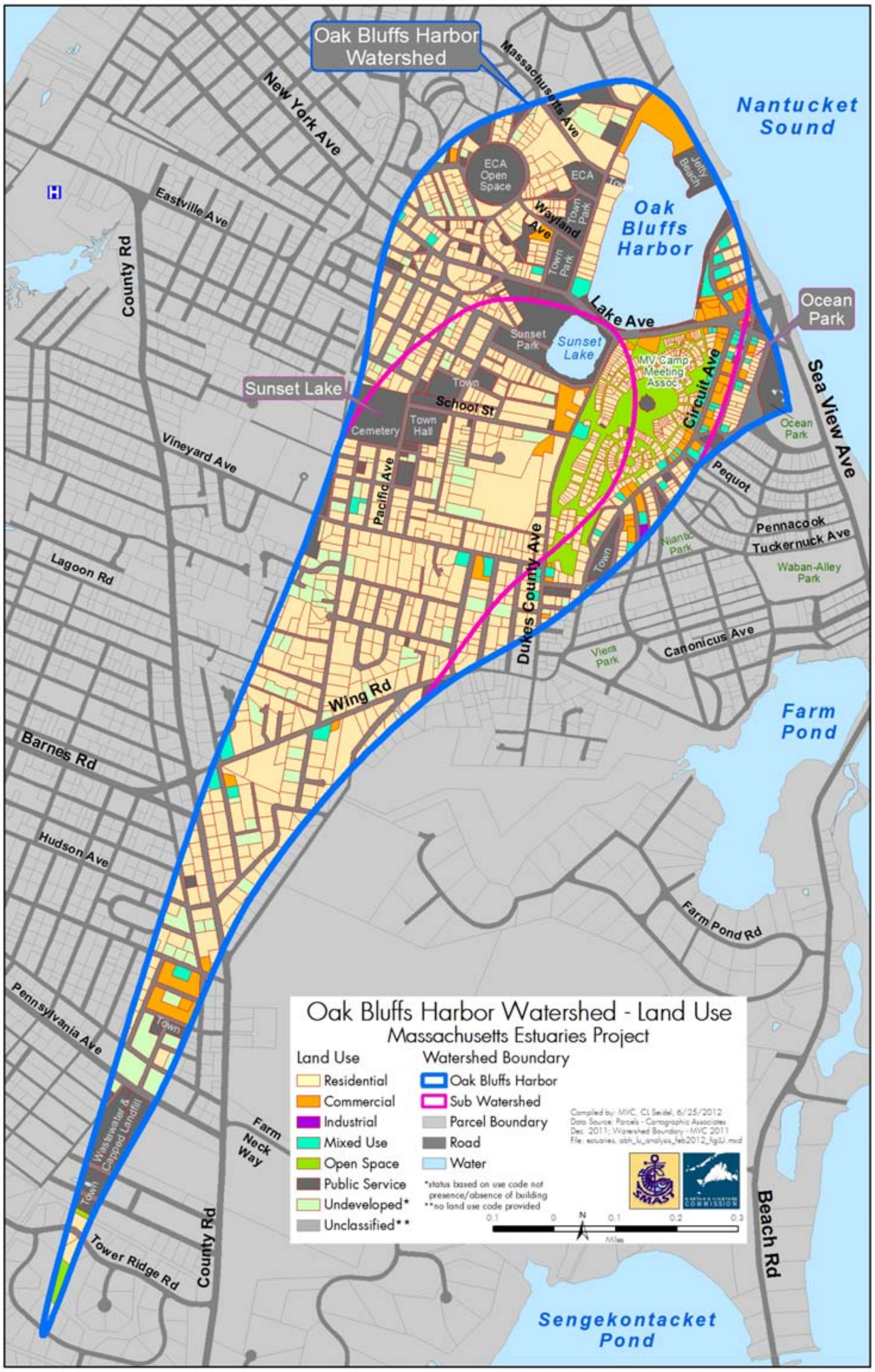


Figure IV-1. Land-use in the Oak Bluffs Harbor watershed. The watershed is completely within the Town of Oak Bluffs. Land use classifications are based on assessors' records provided by the town.

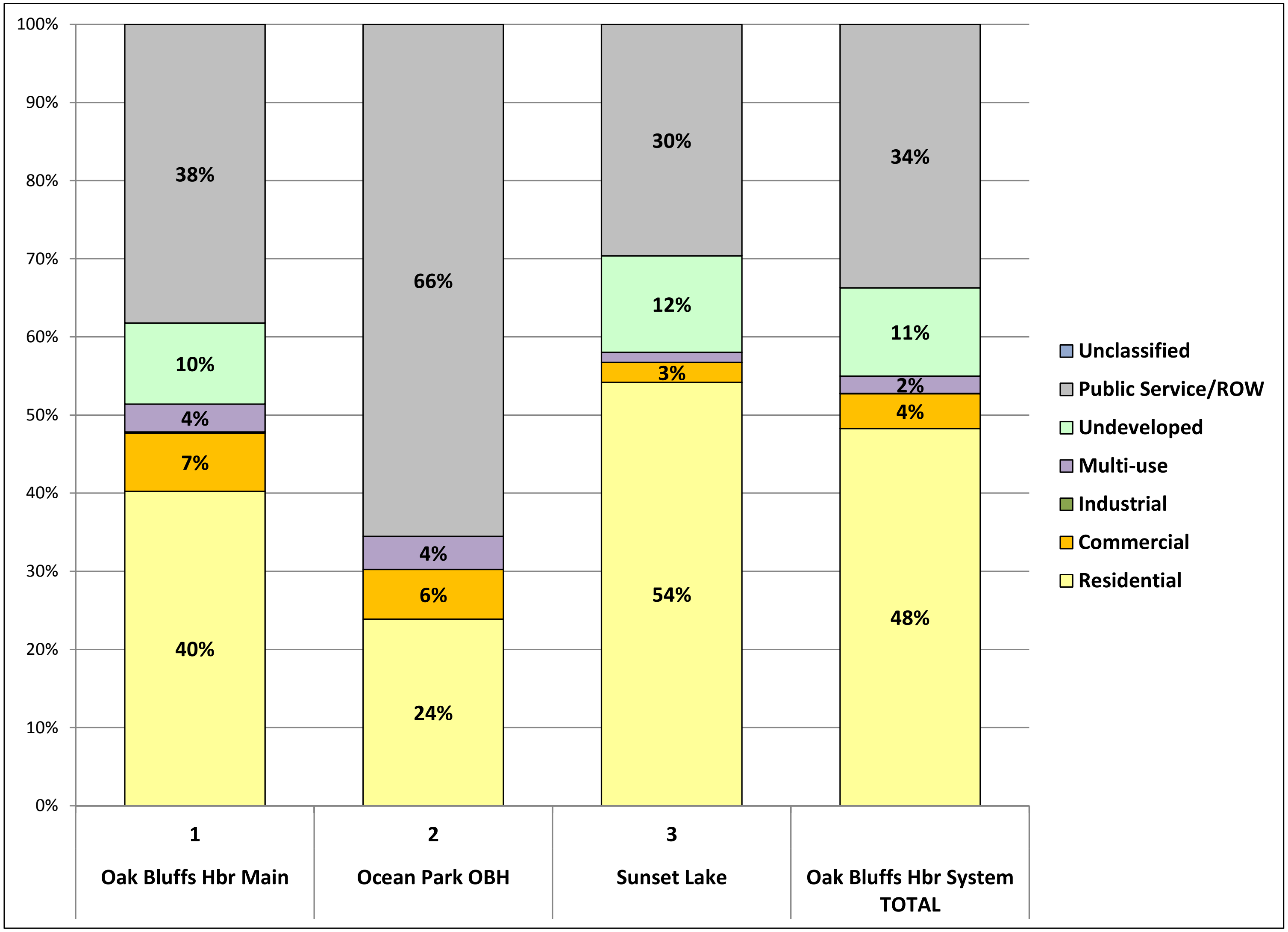


Figure IV-2. Distribution of land-uses areas within the sub-watersheds and whole system watershed to Oak Bluffs Harbor. Land use categories are generally based on assessor's land use grouping recommended by MADOR (2009). Only percentages greater than or equal to 2% are shown.

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 obtained average water use information for properties in the Oak Bluffs Harbor watershed. MVC Staff reviewed four years of water use records (2003-2006) for approximately 1,150 accounts in the watershed. MVC also identified parcels connected to the municipal sewer system; 429 parcels have both measured water use and a sewer connection. Only 38 parcels (3% of developed parcels) were identified as having private wells. Average water use among land use code 101 (single family residences), both sewered and unsewered, is 145 gallons per day. Wastewater-based nitrogen loading from the individual parcels to the overall Oak Bluffs Harbor watershed only occurs from parcels using on-site septic systems; this load is based upon the water-use at each individual parcel, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2). Parcels with sewer connections only contribute nitrogen load based on the treatment at the municipal wastewater treatment facility and the portion of the nitrogen load that is returned to the Harbor via the Ocean Park effluent discharge site.

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

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

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

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

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

While census based population data has limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water 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, it is not used to determine loading rates. This comparison has shown that the larger the watershed the better the match between average water use and occupancy. For example, in the combined Great Pond, Green Pond and Bournes Pond watershed (Town of Falmouth) and the Popponesset Bay/Eastern Waquoit Bay watershed (Towns of Falmouth, Barnstable and Mashpee), which cover large areas and have significant year-round populations, the septic nitrogen loading based upon the census data is within 5% of that from the water use approach. This comparison matches some of the variability seen in census data itself. Census blocks, which are generally 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 Oak Bluffs Harbor and Sunset Lake Embayment System watershed, MEP staff reviewed US Census population values for the Town of Oak Bluffs. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. Based on data collected during the 2010 US Census, average occupancy within Oak Bluffs is 2.28 people per occupied housing unit with 46% year-round occupancy of available housing units; occupancy decreased slightly and year-round occupancy increased slightly from the 2000 Census. Average water use for single-family residences with municipal water accounts in the Oak Bluffs MEP study area is 145 gpd. This flow approximates the wastewater estimate derived by multiplying the state Title 5 estimate of 55 gpd per capita by the average Oak Bluffs occupancy from the 2000 US Census (125 gpd). Multiplying the average measured water use by 0.9 to account for consumptive use results in a study area average of 131 gpd.

The Census-based estimate does not account for the estimated population increase associated with summer visitors to Martha's Vineyard. Estimates of summer populations on Cape Cod and the Islands derived from a number of approaches (*e.g.*, traffic counts, garbage generation, WWTF flows) generally suggest average population increases from two to three times year-round residential populations measured by the US Census. If it is assumed that seasonal properties (51% of the residential units according to the 2010 Census) are occupied at twice the year-round occupancy for three months, the estimated average town-wide water use would be 156 gpd. Given that the average water use for single family residence accounts in the study area is 145 gpd, this analysis suggests that the average water use is reasonably reflective of average wastewater estimates and is a reasonable basis for developing nitrogen loads from wastewater in this watershed.

Water use information exists for 95% of the developed parcels that are not connected to the sewer system in the Oak Bluffs Harbor watershed. Parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (*e.g.*, 101 or 325), have been confirmed as having buildings on them through a review of aerial photographs, and/or do not have a listed account in the water use databases. Of the 38 developed parcels without water use accounts, 23 (61%) are classified as single-family residences (land use code 101). These parcels are assumed to utilize private wells and were assigned the Oak Bluffs study area average water use for single-family residences of 145 gpd in the watershed nitrogen loading modules. Review of commercial properties within the watershed found that, on average, buildings occupied 46% of the property area and these properties have water use of 0.095 gpd per square foot of building area. These commercial water use factors were generally used to estimate water use for non-residential parcels that utilize private wells for drinking water.

Oak Bluffs Wastewater Treatment Facility

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

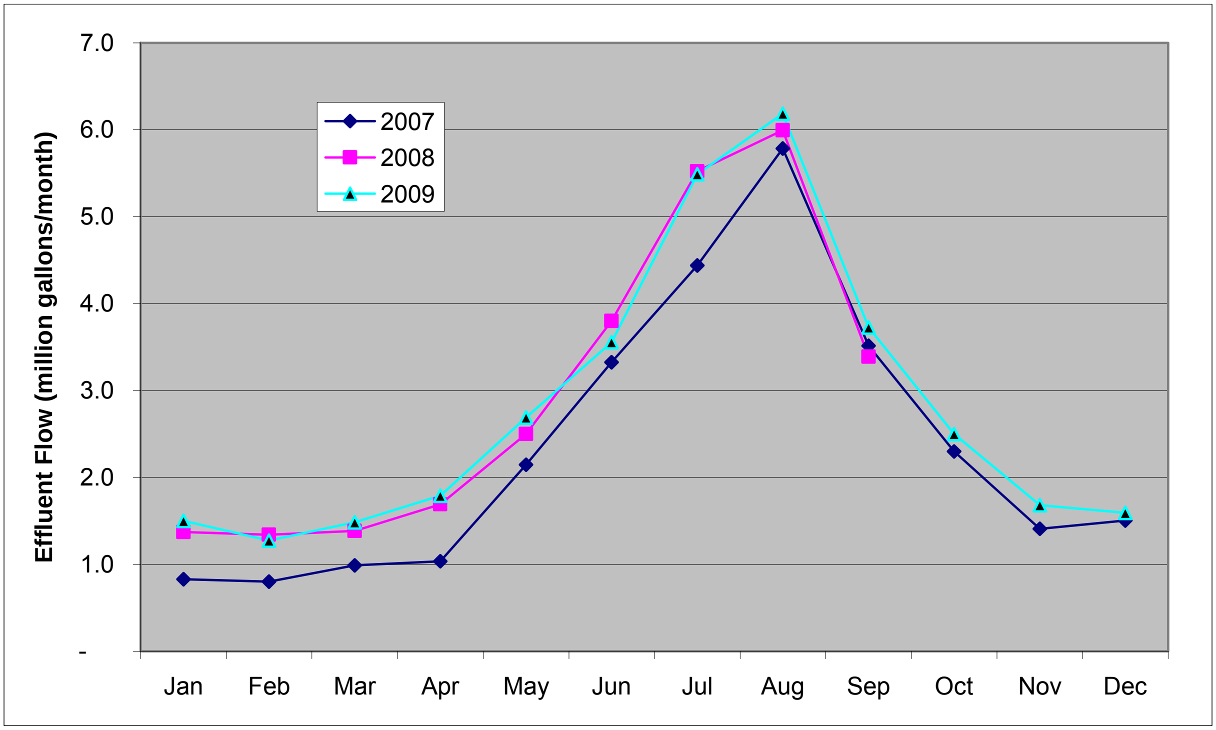
According to the available monitoring data, the Oak Bluffs WWTF produced annual wastewater flows of 28, 27, and 33 million gallons in 2007, 2008, and 2009, respectively. These flows followed a consistent yearly cycle with monthly flows of 0.8 to 1.5 million gallons in January through March followed by increasing flows peaking in July and August of approximately 5 to 6 million gallons per month (Figure IV-3). The only slight difference in flows between the years is an increasing trend over the three years in the “shoulder” months around the peak. The observed seasonal pattern in wastewater flows is common to residential areas throughout Martha's Vineyard, Nantucket and Cape Cod and is consistent with the high percentage of seasonal residences within the Oak Bluffs Harbor watershed.

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

Effluent discharge at Ocean Park has created a permanent groundwater mound. MVC staff review of available groundwater modeling and large-scale slug tests at Ocean Park (Horsley Witten & Wright Pierce, 1997) indicate that the mound is diminished, but sustained, during winter months. Consequently, effluent discharged at Ocean Park flows radially from this mound and creates a change in the groundwater-based watershed to Oak Bluffs Harbor (see Section III). MVC staff has estimated that 30% of the mound and, therefore, 30% of the discharged effluent flow and nitrogen load travel toward Oak Bluffs Harbor. Another 25% discharges to Farm Pond (Howes, *et al.*, 2010), while the remainder discharges to Vineyard/Nantucket Sound. For the purposes of the MEP assessment of Oak Bluffs Harbor, the Oak Bluffs WWTF annually contributes 158 kg of nitrogen to Oak Bluffs Harbor.

According to the provided water accounts, there are 429 parcels within the Oak Bluffs Harbor watershed that are connected to the WWTF collection system. These parcels are 36% of all the parcels in the watershed and their collective annual average flow is approximately 21 million gallons over the four years’ worth of water use data. This average flow is approximately 64% of the total effluent flow from the WWTF in 2009. It is important to note that the average wastewater flow for parcels within the Oak Bluffs Harbor watershed discharging to the WWTF is

134 gpd which compares well with the wastewater discharge from residences determined from water-use records of 131 gpd (see above). The potential nitrogen load from this flow is reduced by 58% due to the improved nitrogen treatment at the WWTF.



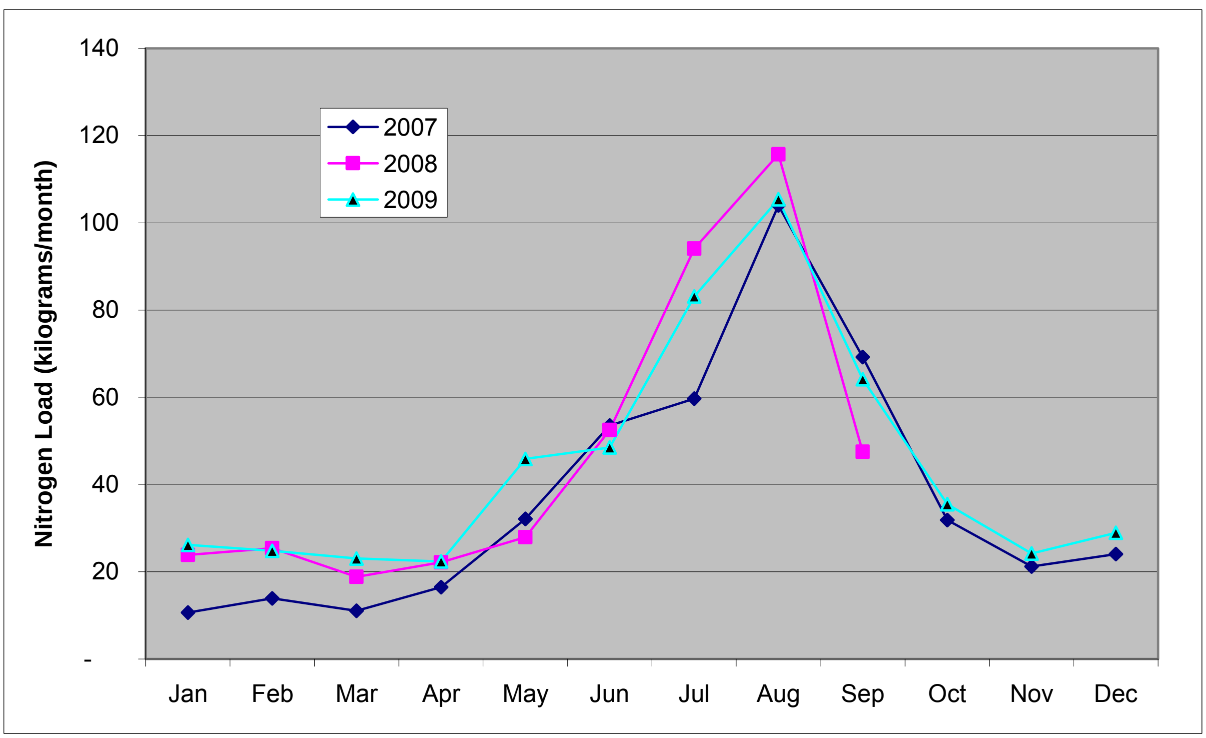


Figure IV-3. Effluent flow and total nitrogen-loading data from Town of Oak Bluffs Wastewater Treatment Facility (2007-09).

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and cranberry bogs, with residential lawns being the predominant source within this category. In order to account for all of these sources in the nitrogen-loading model for the Oak Bluffs Harbor and Sunset Lake Embayment System, MVC staff under the guidance of MEP staff reviewed available information about residential lawn fertilizing practices. No cranberry bogs or other fertilized farmland or golf course areas 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 5,000 sq. ft., and d) only 25% of the nitrogen applied reaches the groundwater (leaching rate). Because many of these assumptions had not been rigorously reviewed prior to the beginning of the MEP, the MEP Technical Staff undertook an assessment of lawn fertilizer application rates and a review of leaching rates for inclusion in the Watershed Nitrogen Loading Sub-Model.

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. 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 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.

In order to develop and adjust the standard MEP lawn fertilizer nitrogen loading factors for the site-specific characteristics of the Oak Bluffs Harbor and Sunset Lake Embayment System watershed, MEP staff reviewed available local surveys and consulted with MVC staff. In 1999, a land use survey on Martha's Vineyard reviewed lawn sizes, including portions of the Oak Bluffs Harbor watershed (MVC, 1999). This survey found that the average lawn size in the study area was 1,820 square feet, while within the Ocean Park sub-watershed, where parcels are smaller, that the average lawn size was only 400 square feet. Review of lawn areas in the Sunset Lake sub-watershed by MEP staff found that lawn sizes are generally larger and determined that 3,500 square feet is an appropriate average for this sub-watershed. The MVC survey also found that average household fertilizer application rates averaged 1 lb N per 1,000 square feet of residential lawn, which is approximately the same as the standard rate determined by the MEP review. MEP Technical staff reviewed these lawn factors with MVC staff and selected appropriate factors in the development of the Oak Bluffs Harbor watershed nitrogen-loading model.

Nitrogen Loading Input Factors: Landfill

The Oak Bluffs landfill is located off County Road and on a watershed boundary between Farm Pond, Sengekontacket Pond, Lagoon 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-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 quantities 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 Oak Bluffs Harbor watershed, MEP staff estimated that the annual nitrogen load from the Oak Bluffs landfill to the Oak Bluffs Harbor watershed is 35 kg/yr.

Nitrogen Loading Input Factors: Other

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

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

Nitrogen Concentrations:	mg/l
Road Run-off	1.5
Roof Run-off	0.75
Direct Precipitation on Embayments and Ponds	1.09
Natural Area Recharge	0.072
Wastewater[1]	
Wastewater Coefficient	23.63
Oak Bluffs WWTF load – current in watershed (kg/yr)	158
Oak Bluffs WWTF load – buildout in watershed (kg/yr)	349
WWTF effluent TN (mg/l)	4.2
Fertilizers[2]:	
Average Residential Lawn Area by sub-watershed	sq ft:
Oak Bluffs Harbor Main	1,820
Ocean Park	400
Sunset Lake	3,500
Residential Watershed Nitrogen Rate (lbs/1,000 sq ft)	1.08
Impervious Surfaces	
Buildings areas for single family residences in watershed (sq ft)	1,315
Road area (sq ft)	measured or 31% of ROW area

Recharge Rates:	in/yr
Impervious Surfaces	42.2
Natural and Lawn Areas	28.7
Water Use/Wastewater:	
Existing developed residential parcels and buildout residential parcels:	Parcel water use or watershed average of 145 gpd
Commercial buildout additions[3]:	95 gpd /1,000 ft2 of building
Commercial building coverage of developed lots and buildout additions[3]:	46%
Town of Oak Bluffs Landfill	
Area of capped solid waste within watershed (acres)	3.4
Estimated TN concentration in landfill plume (mg/l)[4]	3.49
Estimated Total Nitrogen Load (kg/yr)	34.9

Notes:
1 WWTF data based on three years of monitoring and future projected discharge bed capacity
2 Data from 1999 Martha's Vineyard lawn survey and MEP review.
3 Averages based on data in Oak Bluffs Harbor sub-watershed; no industrial build-out additions
4 Based on landfill monitoring data

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 Oak Bluffs Harbor 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 to sub-watersheds, 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 Oak Bluffs Harbor 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 Oak Bluffs Harbor System, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), the Oak Bluffs WWTF, the Oak Bluffs landfill, fertilizers (*e.g.*, residential lawns), impervious surfaces, direct atmospheric deposition to water surfaces, and recharge on natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-4). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model. No natural nitrogen attenuation occurs in the Oak Bluffs Harbor watershed because of the absence of freshwater ponds or streams, however, Sunset Lake, which is a small sub-basin to the Harbor directly connected via a large culvert, does provide some attenuation of watershed load that flows directly to that feature prior to entering Oak Bluffs Harbor. This is common in shallow enclosed basins and salt marsh creeks, where watershed nitrogen enters through groundwater inflows and a portion enters the nitrogen cycle of the basin and the remainder is transported through tidal exchanges to the outer embayment basins. Two tidal flux events were completed in the summer of 2011 to ascertain the nitrogen load from Sunset Lake and this field effort is described in Section IV-2. The measured attenuation was included in the MEP water quality modeling effort.

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 Oak Bluffs Harbor modeling, MVC staff under the guidance of MEP staff reviewed individual properties for potential additional development. This review included assessment of minimum lot sizes based on current zoning, potential additional development on existing developed lots, connection of properties to the municipal water supply system, and an estimate of future effluent discharge from the Oak Bluffs WWTF.

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

		Oak Bluffs Harbor N Loads by Input (kg/yr):								Present N Loads			Buildout N Loads		
Name	Shed ID#	From Wastewater	From WWTF	Landfill	All Fertilizers	From Impervious Surface Runoff	From Atmospheric Deposition	From "Natural" Surfaces	Buildout	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Oak Bluffs Harbor System TOTAL		**3896**	**158**	**35**	**226**	**469**	**180**	**51**	**1092**	**5015**		**5015**	**6106**		**6106**
Oak Bluffs Hbr Main Total		1572	158	0	84	188	0	20	309	2022	0	2022	2331	0	2331
Oak Bluffs Hbr Main	1	1542	0	0	55	173	0	19	118	1790	0	1790	1909	0	1909
Ocean Park OBH	2	30	158	0	29	14	0	1	191	232	0	232	423	0	423
Sunset Lake	3	2323	0	35	142	281	0	31	783	2812	0	2812	3595	0	3595
Oak Bluffs Hbr Main Estuary Surface							157			157	0	157	157	0	157
Sunset Lake Estuary Surface							23			23	0	23	23	0	23

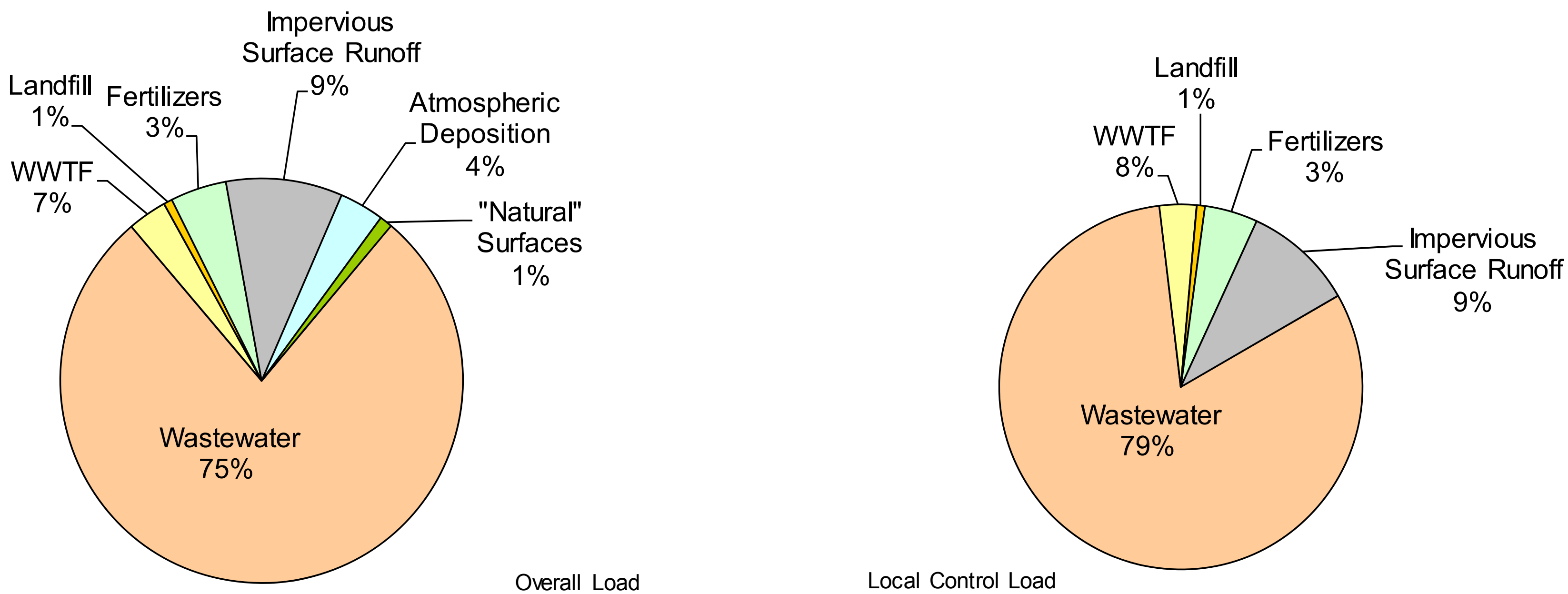


Figure IV-4. Land use-specific unattenuated nitrogen load (by percent) to the overall Oak Bluffs Harbor and Sunset Lake Embayment System watershed. “Overall Load” is the total nitrogen input within the watershed and estuary, while the “Local Control Load” represents only those nitrogen sources that could potentially be under local regulatory control (e.g. managed locally).

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 (*e.g.*, state class land use codes 130 and 131 for residential properties). Properties classified by the Oak Bluffs assessor as "undevelopable" (e.g., codes 132 and 392) were not assigned any development at buildout. Commercially developable properties were not subdivided; the area of each parcel and the factors in Table IV-1 were used to determine a wastewater flow for these properties. Project staff typically reviews these initial results to assess the atypical findings (e.g., additional commercial development on lots in the Ocean Park sub-watershed) and review the results with local experts, who were MVC staff in this case. Any changes and refinements are included in the final MEP buildout assessment.

Based on the buildout assessment completed for this review, there are 165 potential additional residential dwellings and 21,862 square feet of developable commercial land in the Oak Bluffs Harbor watershed. Most of the additional residential parcels (89%) are in the Sunset Lake sub-watershed; no additional residential or commercial parcels are indicated in the Ocean Park sub-watershed. All the parcels included in the buildout assessment of the overall Oak Bluffs Harbor watershed are shown in Figure IV-5.

Nitrogen loads were developed for these buildout additions based largely on existing development factors within the Oak Bluffs Harbor watershed. Table IV-2 presents a sum of the additional nitrogen loads by sub-watershed for the buildout scenario. This sum includes the wastewater, fertilizer, and impervious surface load additions from additional residential dwellings, as well as wastewater and impervious surface loads from projected commercial and institutional buildout additions. Additional buildout single-family residential dwellings were assigned a water use flow of 145 gpd, which is based on the average water use for similar dwellings in the whole of the Oak Bluffs Harbor and Sunset Lake Embayment System watershed. The water use database was also used to determine average water use for commercial properties; water use was determined to be 95 gpd/1,000 sq ft of commercial building. The buildout load also includes the additional nitrogen load estimated for the Oak Bluffs WWTF when it reaches its design flow capacity. MVC staff completed an assessment of future flows based on the current peaking of flows in July and August. This evaluation found that the peak flow of 350,000 gallons per day and the accompanying decreases in the fall, winter, and spring resulted in an annual flow of 73 million gallons. This effluent flow was assigned the current flow-weighted average total nitrogen concentration of 4.2 ppm, resulting in an annual buildout load from the Oak Bluffs WWTF of 1,162 kg with 30% (349 kg/yr) assigned to Oak Bluffs Harbor estuary in the MEP buildout scenario. Overall, buildout additions within the entire Oak Bluffs Harbor and Sunset Lake Embayment System watershed will increase the present unattenuated nitrogen loading rate by 22%.

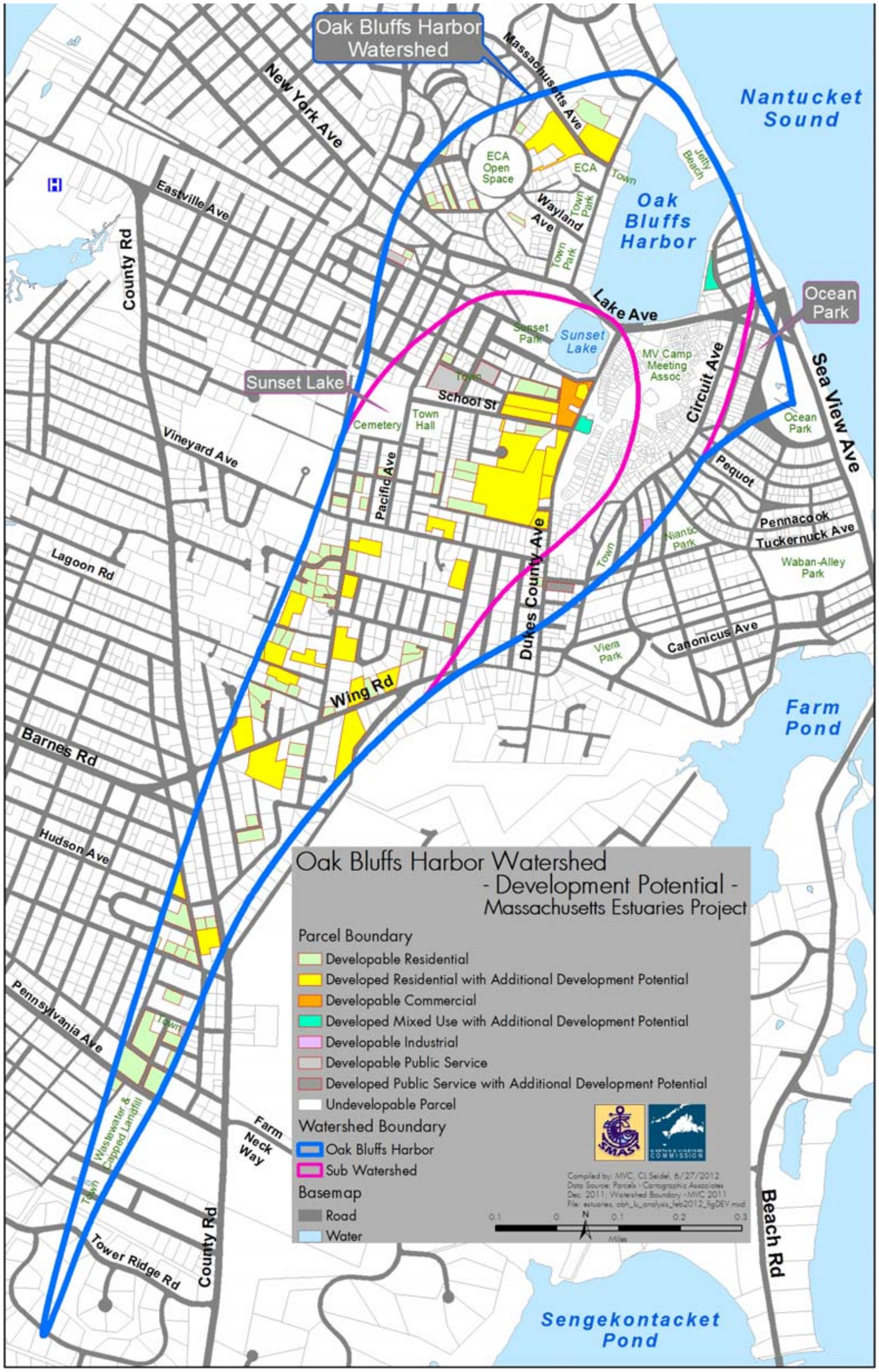


Figure IV-5. Developable Parcels in the Oak Bluffs Harbor watershed, classified by type of potential future use (colors). Nitrogen loads in the buildout scenario are based on additional development assigned to these parcels plus greater effluent discharge from the Oak Bluffs WWTF.

IV.2 ATTENUATION OF NITROGEN IN TRANSPORT TO OAK BLUFFS HARBOR

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

In the case of Oak Bluffs Harbor, even though there are no major freshwater ponds or streams flowing directly into the estuarine system, there is a tidally influenced tributary basin (Sunset Lake) that is directly connected to the Harbor via a culvert. An additional investigation was undertaken by the MEP Technical team to quantify the nutrient flux associated with Sunset Lake and determine if there is any measurable nitrogen attenuation (or possibly net summertime nitrogen release) associated with this feature.

A total of 2 tidal nutrient flux samplings were conducted in 2011 on June 30 and August 1 at the Lake Avenue culvert. Each sampling took place over a single complete tidal cycle beginning approximately 1 hour before low tide and ending approximately 1 hour after the following low tide. Before each tidal flux, it was determined that there was no precipitation for at least one complete tidal cycle prior to the first sampling to ensure that water and nutrient flux data would not be biased by rain-related flows. Water samples were collected at the culvert at regular intervals over the course of the tidal cycle. Samples were analyzed for salinity, Chlorophyll a and total nitrogen. Flood and ebb current velocity measurements and culvert cross-section water depths were made concurrently with water sample collections at the culvert to determine volumetric flow through the culvert throughout both flood and ebb tides. These flow data were then interpolated to yield a detailed record of total volumetric flow into and out of Sunset Lake to quantify the interaction between the Lake and the Harbor. Total flow out was calculated from slack high tide to the point at which the tidal height during ebb reached the same level as that recorded at the previous slack low tide to correct for any tidal asymmetry, as measured by a tide gauge (Figure IV-6) deployed up-gradient of the Lake Avenue culvert.

Volumetric exchange during flood and ebb tides was used to calculate the mass flux of nitrogen into and out of Sunset Lake on each of the 2 sampling dates. Data from each collected water sample was paired with the corresponding flow rate to calculate a mass flux of each constituent for each time point during a tidal cycle. These results were interpolated to yield a total mass flux for the entire tidal cycle (i.e. the total out minus the total in = net flux) (Table IV-3).

Figure IV-6. Location of tidal flux investigation between Sunset lake and Oak Bluffs Harbor in order to quantify flow and associated nutrient loading to the Harbor.

During the August 1, 2011 tidal flux, maximum flood stage at slack high was approximately 0.5 feet higher than that measured during the June 30, 2011 tidal flux event and as such the volume of water in and out of Sunset Lake from Oak Bluffs Harbor was higher during the August 2011 event compared to the June 2011. Total tidal volumetric exchange over the 2 tidal cycles measured ranged from 7,720 cubic meters on June 30 to 12,065 cubic meters on August 1 during flooding tides (Tables IV-3 and IV-4) compared to ebbing tides, which ranged from 7,706 cubic meters on June 30 to 14,208 cubic meters on August 1 (Table IV-3). Water flux during tidal ebb was of a longer duration than during tidal flooding. Each of the tidal cycles measured showed a greater volume of water exiting Sunset Lake on the ebbing tide than entering on the preceding flooding tide. This volumetric difference, results from the entry of freshwater from groundwater seepage into Sunset Lake. The observations and volumetric effect of freshwater on tidal inflow versus outflow has been documented for a variety of salt marsh and embayment systems on Cape Cod (Millham and Howes 1994, Smith 1999, Valiela et al. 1978). The result of the interaction of freshwater inflows and tidal hydrodynamics is that the volume of water on the ebb tide is greater than on the flood tide (Table IV-3). While it is very difficult to accurately determine groundwater inflow to a tidal basin from the volumetric difference between total flood and ebb flows, the average groundwater inflow determined from the land-use model and local recharge rates of 1870 $m^3 d^{-1}$ (~935 per tide) is consistent with the range of flows measured by the tidal studies. Similarly, it is possible to estimate flood tide volume from the tidal prism (tide range and surface area) on each date. Again, the estimated flood tide volume was within 6%-9% of that directly measured. Both of these comparisons (groundwater and tidal prism) increase confidence that the tidal surveys were accurately representing tidal exchanges within Sunset Lake. However, it must be cautioned that additional surveys are desirable if more refined attenuation rates are needed to develop management alternatives for this basin.

Based upon the tidal volume data and the time-series total nitrogen measurements collected over each tidal cycle, the total nitrogen mass entering and leaving Sunset Lake was determined. Total Nitrogen (TN) is the sum of all organic and inorganic forms of N and therefore accounts for transformations by phytoplankton of inorganic nitrogen to organic forms. Based upon this analysis there was a net export of TN on both dates (Tables IV-3). However, from the limited data (only 2 surveys) it may be that TN export may be affected by the tide range, as there was a relatively large difference in export on the 2 dates. The potential effect would be that export on the order of the August 1 survey would be more common. Given this uncertainty the MEP Technical Team chose a conservative estimate of export for the purpose of the water quality modeling. As such it was determined that when the TN load out of Sunset Lake was compared to the TN load entering Sunset Lake from the associated sub-watershed, Sunset Lake was generating approximately 70 percent attenuation (higher than expected given past attenuation measures completed by the MEP in other systems). Based on professional judgment, a 50 percent attenuation was assigned to the TN load prior to its discharge to Oak Bluffs Harbor with the thought that 50 percent attenuation is more conservative and also takes into account statistical issues associated with determining export as the difference between 2 large exchanges (flood mass - ebb mass). Moreover, this level of nitrogen attenuation is consistent with the structure of Sunset Lake, it being dominated by organic rich sediments and fringing marsh capable of attenuating nitrogen. As Sunset Lake is a brackish component of Oak Bluffs Harbor, the MEP analysis of Sunset Lake addressed the 50% attenuation of nitrogen passing through the basin (i.e. half of the 7.70 kg/d from the watershed) by attributing the reduction via a benthic flux term within the WQ model using the following calculation, 7.70 kg x 0.50 / 17,619 m2 x 1000000 = -218.5 mg/m2/day which was assigned as benthic flux for the basin. If additional tidal flux investigations are completed on Sunset Lake to refine the attenuation value, this could be integrated into the model as management options are developed and evaluated by the Town of Oak Bluffs in the future.

Table IV-3. Results of Sunset Lake tidal flux investigation to quantify exchange of water and nutrients between the tidally influenced Sunset Lake and Oak Bluffs Harbor. It was possible to perform a simplified tidal prism estimate of the volume of flood water on each date, providing an independent quality assurance check on the direct integrated flow measurements. Note that the average freshwater inflow to Sunset Lake is ~930 m^3 per tide. The difference in flood tide volumes related to the different tide ranges between the 2 dates.

	August 1, 2011		June 30, 2011	
Sunset Lake	**Water m3**	**TN (g)**	**Water m3**	**TN (g)**
Flood Tide	12,065	6,197	7,720	3,297
Ebb Tide	14,208	7,334	8,078	3,980
Net Flux	**2,143**	**1138**	**357**	**683**
Tidal Prism Derived Flood Tide Volume of Flood Tide (QA check)				
Volume Flood Tide (m3) =	11,059		7,300	
% difference =	9%		6%	

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

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

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

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation across the embayment basin will result in significant errors in determination of the threshold nitrogen loading to the Oak Bluffs Harbor 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 Oak Bluffs Harbor and Sunset Lake Embayment System, sediment samples were collected and incubated under *in situ* conditions in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August). Sediment samples (8 cores) were collected from 7 sites (Figure IV-7) in July-August 2006, focusing on obtaining an areal distribution that would be representative of nutrient fluxes throughout the Harbor. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The number of core samples from each site (Figure IV-7) per incubation are as follows:

Oak Bluffs Harbor System Benthic Nutrient Regeneration Cores

- OBH-1 1 core (Main Basin)
- OBH-2 1 core (Main Basin)
- OBH-3 1 core (Main Basin)
- OBH-4 1 core (Main Basin)
- OBH-5 1 core (Main Basin)
- OBH-6/7 2 cores (Main Basin)
- OBH-8 1 core (Main Basin)

Sampling was distributed throughout the harbor such that the results for each site could be combined to calculate the net nitrogen regeneration rates for the water quality modeling effort.

Sediment-water column exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1998) for nutrients and metabolism. Upon return to the field laboratory (Town of Oak Bluffs Department of Public Works), the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and orthophosphate (Murphy and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-

20°C) for assay of nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON (D'Elia *et al.* 1977). Rates were determined from linear regression of analyte concentrations through time.

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

Figure IV-7. Oak Bluffs Harbor System locations (yellow diamonds) of sediment sample collection for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-3.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

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

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

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

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

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

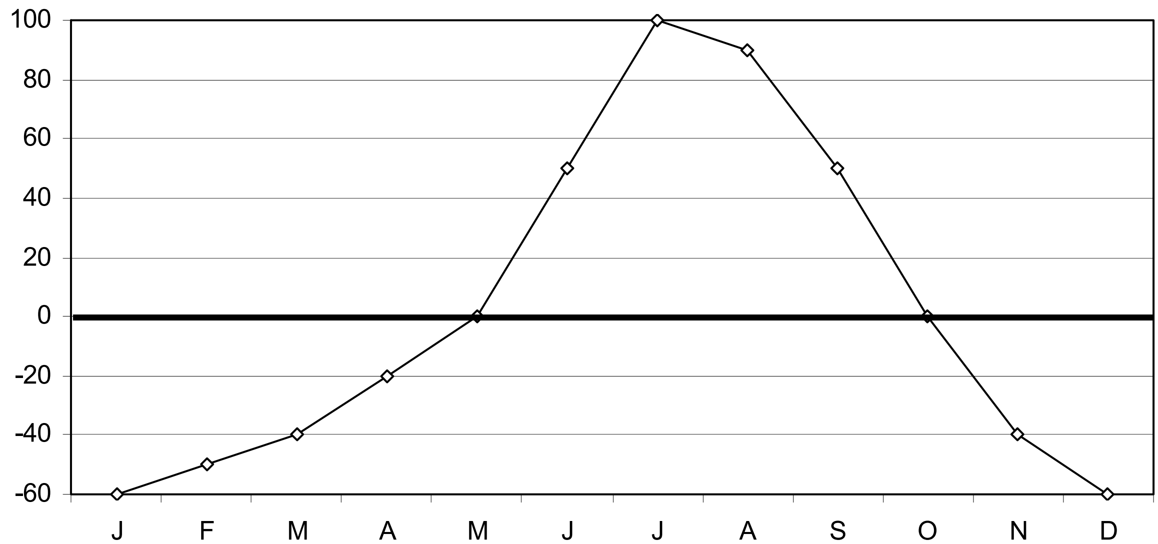


Figure IV-8. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

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

Rates of net nitrogen release or uptake from the sediments within the Oak Bluffs Harbor and Sunset Lake Embayment System were comparable to other embayments of similar depth and configuration in southeastern Massachusetts. The average summertime rate of net nitrogen release throughout the Harbor basin, 85 mg N m^{-2} d^{-1}, was slightly lower than the similarly configured tidal basins of comparable size and tide range in the Town Harwich, Allens, Saquatucket and Wychmere Harbors with rates of 102, 132 and 114 mg N $m^{-2}d^{-1}$, respectively. These basins, like Oak Bluffs Harbor, have low velocities within the basin and are connected directly to offshore waters of Nantucket/Vineyard Sound via a relatively short tidal inlet/channel. In addition, all have comparable watershed nitrogen loading rates and freshwater inflows dominated by groundwater. The measured rates of nitrogen release are also similar to other similarly sized enclosed sub-basins of Cape Cod estuaries, such as the Pleasant Bay sub-basins of Meetinghouse Pond, Areys Pond, Paw Wah Pond and Round Cove, 79.5, 107.3, 120.7 and 139 mg N m^{-2} d^{-1}, respectively.

Net nitrogen release rates for use in the water quality modeling effort for the Oak Bluffs Harbor basin (Section VI) are presented in Table IV-4. Overall, the measured rates of sediment regeneration within this estuary are consistent with most other systems assayed by the MEP throughout southeastern Massachusetts. The sediments within Oak Bluffs Harbor 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 these systems and their flushing rates (cf. Section VI).

Table IV-4. Rates of net nitrogen return from sediments to the overlying waters of the Oak Bluffs Harbor and Sunset Lake Embayment System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July - August rates.

	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			
Location	**Mean**	**S.E.**	**N**	**i.d. ***
Oak Bluffs Harbor and Sunset Lake Embayment System				
Main Harbor Basin	85	45	8	OBH 1-8

* Station numbers refer to Figure IV-7.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This hydrodynamic study, funded by the Massachusetts Division of Ecological Restoration, was performed for Oak Bluffs Harbor, located within the town of Oak Bluffs, on the island of Martha's Vineyard in Massachusetts. It is the receiving basin of groundwater flow from much of the densely developed Oak Bluffs area. A topographic map detail in Figure V-1 shows the general study area. Oak Bluffs Harbor is moderately deep, man-made coastal embayment with narrow and deep opening to Nantucket Sound. The average depth of the main Harbor basin bottom is -7 feet mean (NAVD). Approximately 2400 feet of the southern perimeter of the main harbor basin has a vertical sheet-pile wall in place (Figure V-2). The harbor is attached to a sub-embayment, Sunset Lake, by a large culvert. The mean depth of this sub-embayment is -1.5 feet (NAVD). The total surface coverage of the Oak Bluffs Harbor Embayment System is approximately 36.3 acres, which includes 4.9 acres of Sunset Lake.

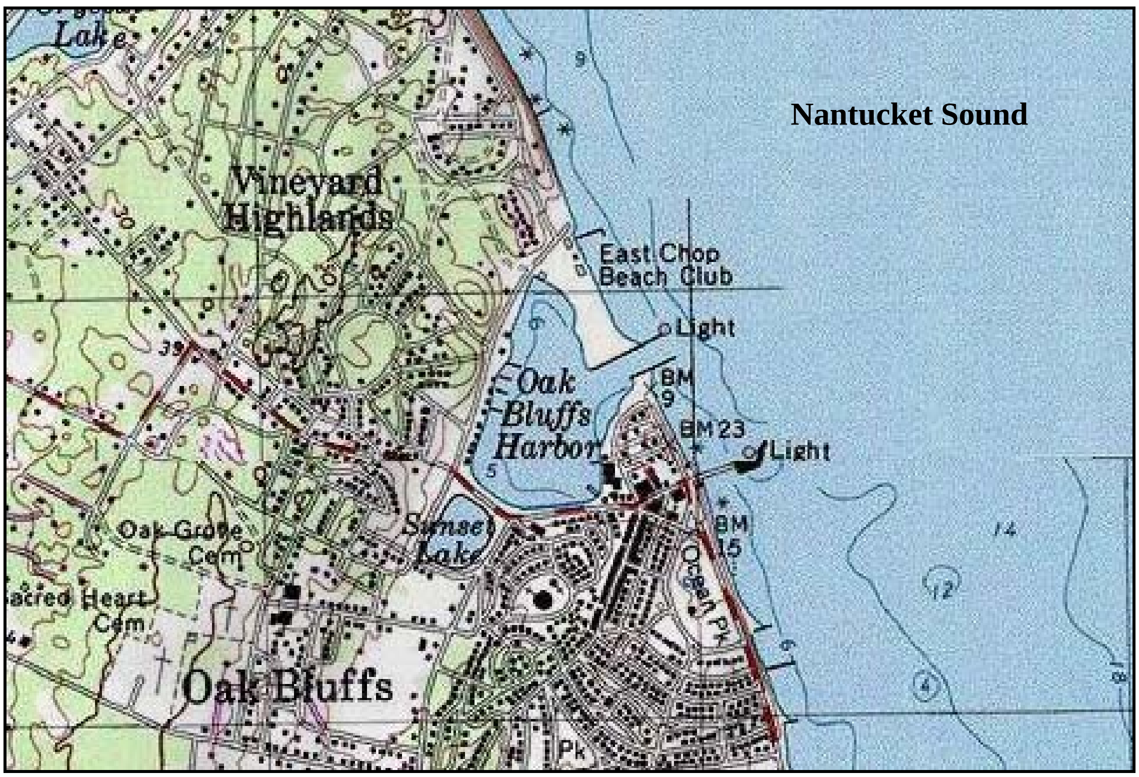


Figure V-1. Topographic map detail of Oak Bluffs, including Oak Bluffs Harbor and Nantucket Sound.

Circulation in the Harbor is dominated by tidal exchange with Nantucket Sound. From measurements made in the course of this study, the average tide range offshore from the harbor is 1.8 feet. As indicated by the lack of significant tide range attenuation at Sunset Lake, tidal flushing is generally very efficient throughout the entire Harbor system. This also indicates that both the culvert between Oak Bluffs Harbor and Sunset Lake and the inlet to the harbor do little to restrict tidal flow. Only occasionally does the inlet accumulate sediments to the point that it must be dredged to maintain navigability and flushing.

The hydrodynamic study of the Oak Bluffs Harbor and Sunset Lake Embayment System proceeded as two component efforts. In the first portion of the study, bathymetry and tide data were collected in order to accurately characterize the physical system, and to provide data necessary for the modeling portion of the study. The bathymetry survey of the Oak Bluffs Harbor inlet was performed to determine the inlet depths. Digital bathymetry data, used to create NOAA navigational chart number 13238, was used to model the bathymetry of the remaining area. In addition, tides were recorded at 3 stations for 34 days. These tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of Oak Bluffs Harbor and its attached sub-embayment was developed in the second portion of this study. Using the bathymetry survey data and the NOAA chart, a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data from Nantucket Sound were used to define the open boundary condition that drives the circulation of the model, and data measured within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the real, physical system.

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

Figure V-2. View of Oak Bluffs Harbor main basin bordered by a vertical sheet-pile bulkhead.

V.2 DATA COLLECTION AND ANALYSIS

The field data collection portion of this study was performed to characterize the physical properties of Oak Bluffs Harbor. Bathymetry data were collected throughout the system so that it could be accurately represented as a computer hydrodynamic model and flushing rates could be determined for the system. In addition to the bathymetry, tide data were also collected throughout the Harbor system (including both Sunset Lake, and the area outside of the harbor inlet in Nantucket Sound), in order to run the circulation model with real tides, and also to calibrate and verify its performance.

V.2.1 Bathymetry Data

A detailed bathymetric survey of the Oak Bluffs Harbor inlet was performed on September 7, 2010 (CLE, 2010). A fathometer was used to take continuous soundings of the bottom as the survey vessel moved through the water. Positioning data were collected using a differential GPS. The actual survey paths followed by the survey craft are shown in Figure V-3. Elevations along the remainder of Oak Bluffs Harbor and Sunset Lake were determined using bathymetry data collected for the creation of NOAA chart #13238.

The resulting bathymetric surface created by interpolating the survey and chart data to a finite element mesh is shown in Figure V-4. Inlet bathymetric soundings were tide corrected using tide data collected in the system. The data were all rectified to the NAVD 88 vertical datum using benchmarks provided by the town. The benchmark elevations were confirmed using an RTK GPS system.

Results from the bathymetry investigation show that the deepest parts of Oak Bluffs Harbor are the southeast and east sections neighboring the harbor inlet. The deepest depth measured in the course of the bathymetric survey is -17.3 feet NAVD immediately southwest of the harbor inlet. The mean depth of the harbor inlet is -9 feet NAVD, the mean depth of the harbor basin is -7 feet NAVD and the mean depth of Sunset Lake is -1.5 feet.

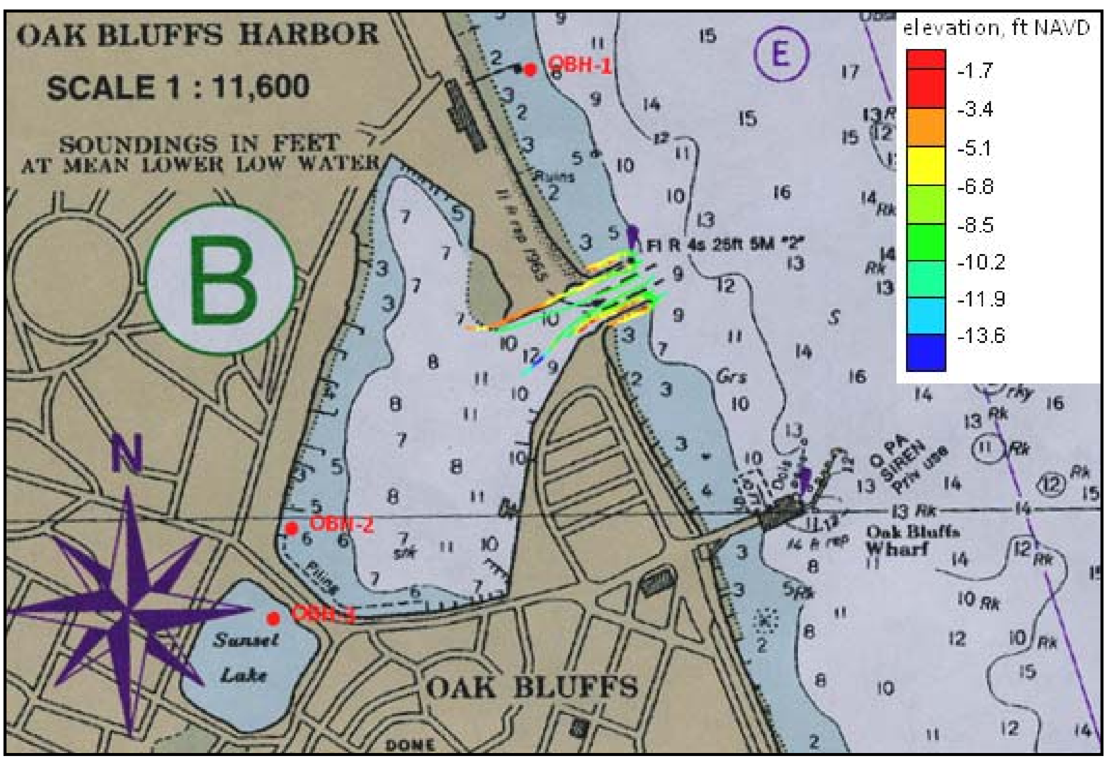


Figure V-3. Transects from the September 7, 2010 survey of the Oak Bluffs Harbor Inlet (CLE, 2010) and NOAA nautical chart #13238. Red markers show the locations of the tide recorders deployed for this study (OBH-1 Nantucket Sound, OBH-2 Inner Harbor, OBH-3 Sunset Lake)

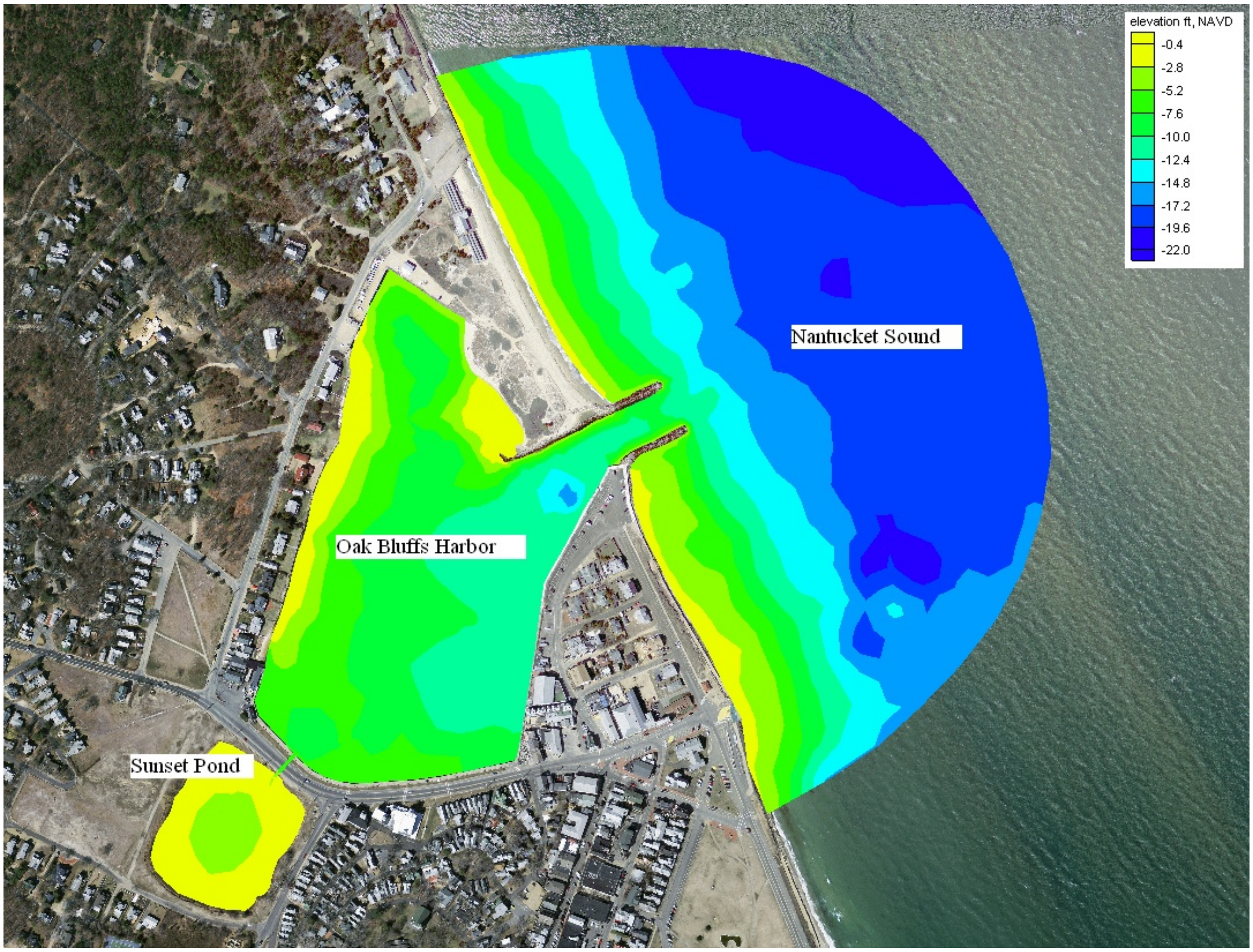


Figure V-4. Bathymetry data interpolated to the finite element mesh used with the RMA-2 hydrodynamic model. Contours represent the bottom elevation relative to mean low water (NAVD). The data sources used to develop the grid mesh are the September 7, 2010 survey of the inlet, and the NOAA chart data.

V.2.2 Tide Data Collection and Analysis

Tide data records were collected concurrently at three gauging stations shown in Figure V-2, located in Nantucket Sound (OBH-1), at the inner harbor (OBH-2), and in Sunset Lake (OBH-3). The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 34-day period between March 30 and May 2, 2012. The elevation of each gauge was surveyed relative to the NAVD vertical datum. The Nantucket Sound tide record was used as the open boundary condition of the hydrodynamic model. Data from inside the system were used to calibrate the model.

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

Plots of the tide data from the three gauges are shown in Figure V-5 for the entire 30-day deployment. The spring-to-neap variation in tide range is discernible in these plots. The data record during a period of neap tides shows a minimum range of approximately 0.7 feet; occurring on April 21. Between April 6 and April 13, there is a period of spring tides, where the maximum range of 3.2 feet occurs on April 11.

A visual comparison between tide elevations offshore and at the different stations in the system shows that the tide amplitude does not significantly change between stations, even within Sunset Lake. This lack of reduction in tidal amplitude throughout the system, described as tidal attenuation, indicates a lack of flow restriction from both the culvert connecting Oak Bluffs Harbor to Sunset Lake and the inlet into the harbor.

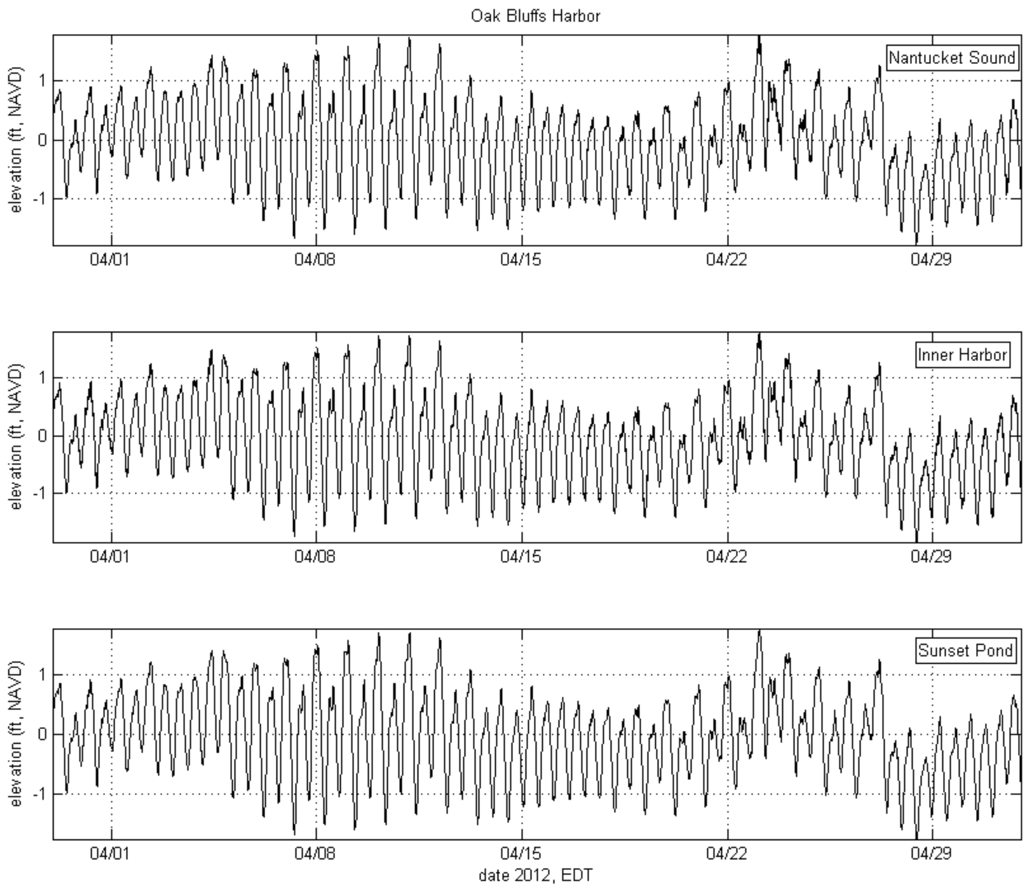


Figure V-5. Plots of observed tides for stations in Oak Bluffs Harbor, for the 34-day period between March 30 and May 2, 2012. All water levels are referenced to the NAVD vertical datum.

To better quantify the changes to the tide from the inlet to the inside of the system, the standard tide datums were computed from the 34-day record. These datums are presented in Table V-1. For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data was available; however, these datums still provide a useful comparison of tidal dynamics within the system. The Mean Higher High (MHH) and Mean Lower Low (MLL) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (NAVD) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW.

Table V-1. Tide datums computed from 30-day records collected offshore and in the Oak Bluffs Harbor and Sunset Lake Embayment System in April 2012. Datum elevations are given relative to the NAVD vertical datum.

Tide Datum	Nantucket Sound (feet)	Inner Harbor (feet)	Sunset Lake (feet)
Maximum Tide	1.8	1.80	1.8
MHHW	1.00	1.00	1.00
MHW	0.8	0.75	0.8
MTL	-0.1	-0.15	-0.1
MLW	-1.0	-1.06	-1.0
MLLW	-1.2	-1.24	-1.2
Minimum Tide	-1.8	-1.83	-1.8
Mean Range	1.8	1.8	1.8

Frictional damping not only affects the range of the observed tide, it also causes a time lag in the arrival of high and low tide. Significant damping is not evident through both Table V-1; showing the similar mean tide range throughout the system and Figure V-6; showing that damping in not significant within system through both attenuation and time lag. Table V-1 shows the mean tide range observed within Oak Bluffs harbor is 0.03 feet larger than the range observed within Nantucket sound. This likely does not represent what is present in the harbor system as tidal amplitude is expected to decrease within the system. This small discrepancy is comparable to the accuracy of the tidal measurements (0.032 ft) and is acceptable for the purpose of modeling tidal hydrodynamics within the harbor.

A more thorough harmonic analysis of the tidal time series was also performed to produce tidal amplitude and phase of the major tidal constituents, and provide assessments of hydrodynamic 'efficiency' of the system in terms of tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each system.

A harmonic analysis was performed on the time series from each gauge location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The observed astronomical tide is the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-7. The amplitudes and phase of 21 known tidal constituents result from this procedure. Table V-2 presents the amplitudes of seven tidal constituents computed for the Oak Bluffs Harbor station records. The M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an offshore amplitude of 0.34 feet. The total range of the M_2 tide is twice the amplitude, or 0.68 feet.

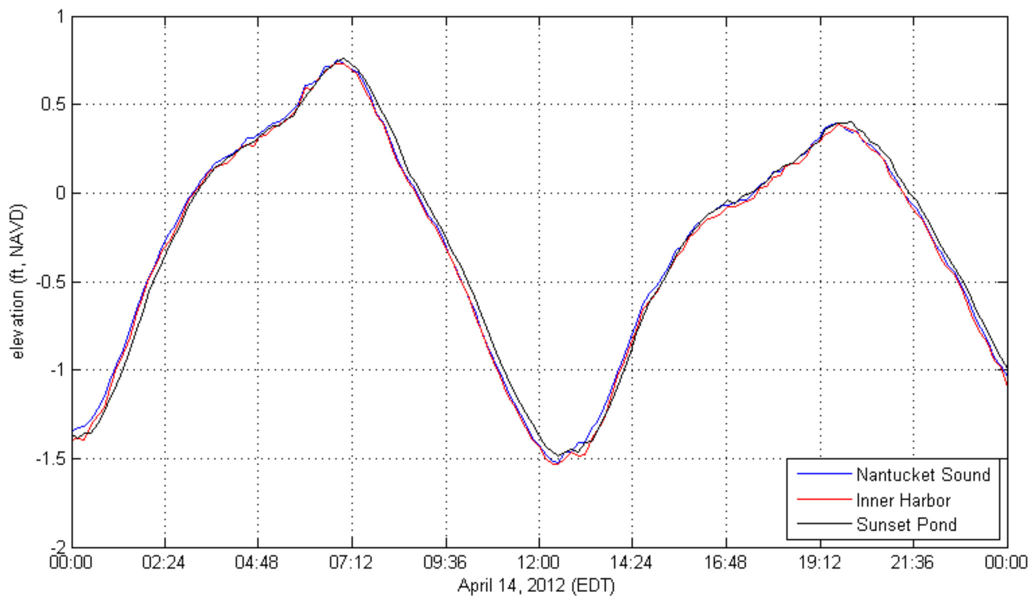


Figure V-6. One-day tide plot showing tides measured in Nantucket Sound and at stations in the Oak Bluffs Harbor and Sunset Lake Embayment System. Demonstrated in this plot is the lack of frictional damping by the culvert connection between Sunset Lake and Oak Bluffs Harbor.

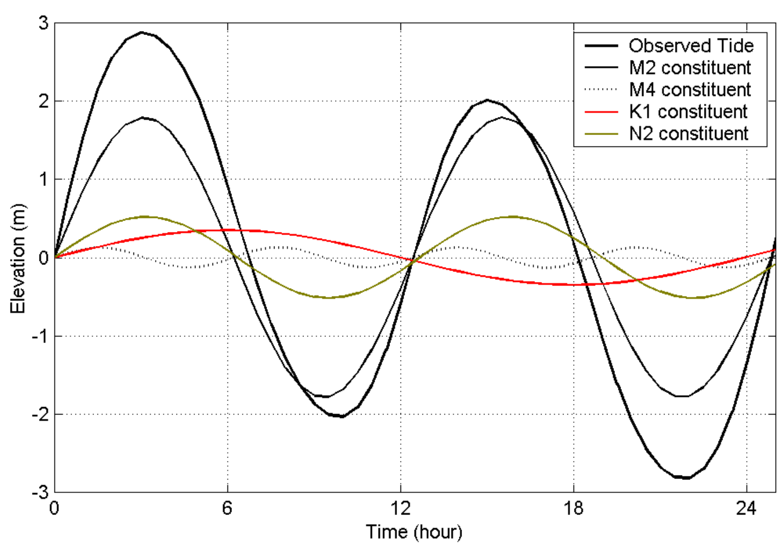


Figure V-7. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-2. Tidal Constituents computed for tide stations in the Oak Bluffs Harbor and Sunset Lake Embayment System and offshore in Nantucket Sound, March 30 to May 2, 2012.							
	Amplitude (feet)						
Constituent	M_2	M_4	M_6	S_2	N_2	K_1	O_1
Period (hours)	12.42	6.21	4.14	12	12.66	23.93	25.82
Nantucket Sound	0.34	0.07	0.02	0.03	0.12	0.10	0.11
Oak Bluffs Harbor	0.35	0.08	0.03	0.03	0.12	0.10	0.11
Sunset Lake	0.35	0.07	0.03	0.03	0.12	0.10	0.11

The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.10 and 0.11 feet respectively. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, also contribute to the total tide signal, with amplitudes of 0.03 feet and 0.12 feet, respectively. The M_4 and M_6 tides are higher frequency harmonics of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water.

Generally, it can be seen that as the total tide range is not attenuated through the system as there is no corresponding reduction in the amplitude of the individual tide constituents. This indicates that frictional damping within the system is small. Several constituents are shown to increase at the station within Oak Bluffs Harbor when compared to Nantucket Sound station. This is likely a result of the same measurement error discussed earlier.

Though there is little change in constituent amplitudes across the harbor system, the phase change of the tide is seen from the results of the harmonic analysis. Table V-3 shows the delay of the M_2 at different points in the Oak Bluffs Harbor and Sunset Lake Embayment System, relative to the timing of the M_2 constituent in Nantucket Sound, outside of the harbor entrance. Between the offshore and the inner harbor stations, there is only a 1.9 minute delay in the M_2. While between the offshore and Sunset Lake stations, there is a 27.8 minute delay. These are not large delays, considering that the period of this constituent is more than 12 hours and they further indicate that damping is small within the system.

Table V-3. M_2 tidal constituent phase delay (relative to Nantucket Sound) for gauge locations in the Oak Bluffs Harbor and Sunset Lake Embayment System, determined from measured tide data.	
Station	Delay (minutes)
Oak Bluffs Harbor	1.9
Sunset Lake	27.8

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

The results of an analysis to determine the energy distribution (or variance) of the measured water elevation records for the gauge records in Oak Bluffs Harbor compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 21 constituents determined by the harmonic analysis) is presented in Table V-4. Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary. Figure V-8 shows the comparison of the measured tide from Nantucket Sound, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

Table V-4 shows that the variance of tidal energy was similar in all signals. The analysis also shows that tides are responsible for approximately 83% of the water level changes in Nantucket Sound and Oak Bluffs Harbor. This indicates that the hydrodynamics of the system is influenced predominantly by astronomical tides and the lack of a significant difference between stations is a further indication of a good overall flushing within the system.

Table V-4. Percentages of Tidal versus Non-Tidal energy for stations in the Oak Bluffs Harbor and Sunset Lake Embayment System and Nantucket Sound, March and April 2012.

TDR Location	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Nantucket Sound	0.1	83.1	16.9
Oak Bluffs Harbor	0.1	82.6	17.4
Sunset Lake	0.1	83	17

V.3 HYDRODYNAMIC MODELING

For the modeling of the Oak Bluffs Harbor and Sunset Lake Embayment System, Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in the Pond. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2 for numerous flushing studies on Cape Cod, including West Falmouth Harbor, Popponesset Bay, Chatham embayments (Kelley, *et al*, 2001), Falmouth "finger" Ponds (Howes *et al*, 2005), Three Bays (Kelley *et al*, 2003) and Barnstable Harbor (Wood, *et al*, 1999).

V.3.1 Model Theory

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

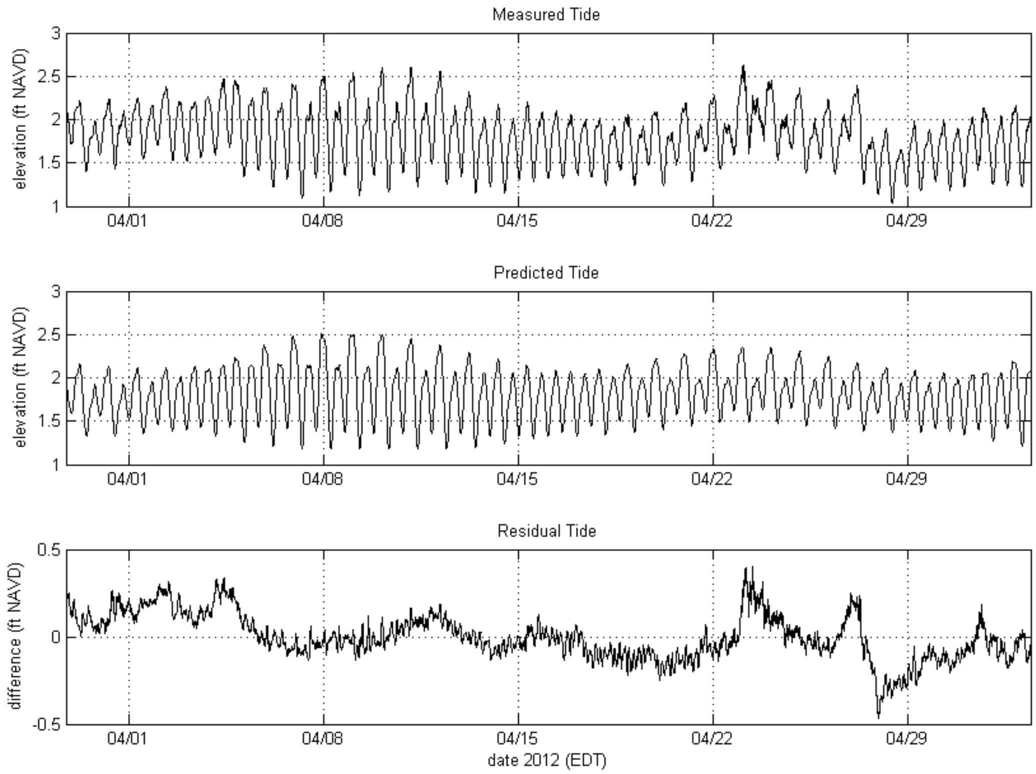


Figure V-8. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 21 individual tide constituents determine in the harmonic analysis of the Nantucket Sound gauge data, collected offshore of Oak Bluffs Harbor. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (r=m-p).

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

The extent of each finite element grid was generated using 2009 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of the Oak Bluffs Harbor grid based on the tide gauge data collected offshore in Nantucket Sound. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several model calibration simulations for the system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. 2009 digital aerial orthophotos, the NOAA chart bathymetry and the 2012 bathymetry survey data were imported to SMS, and a finite element grid was generated to represent the estuary. The aerial photograph was used to determine the land boundary of the system. The bathymetry data were interpolated to the developed finite element mesh of the system. The completed grid consists of 3117 nodes, which describe 1190 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth is -22ft (NAVD) along the open boundary of the grid in Nantucket Sound. The completed grid mesh of the Oak Bluffs Harbor and Sunset Lake Embayment System is shown in Figure V-9.

Included in the model is the box culvert between the main harbor basin and Sunset Lake (Figure V-10). This culvert has a width of 10 feet and an invert elevation of -3.1 feet NAVD on the pond side.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Oak Bluffs Harbor. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Grid resolution is generally governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution is employed where complex flow patterns are expected, generally near the inlet and the culvert between Sunset Lake and the Inner harbor. Appropriate implementation of wider node spacing and larger elements reduces computer run time with no sacrifice of accuracy.

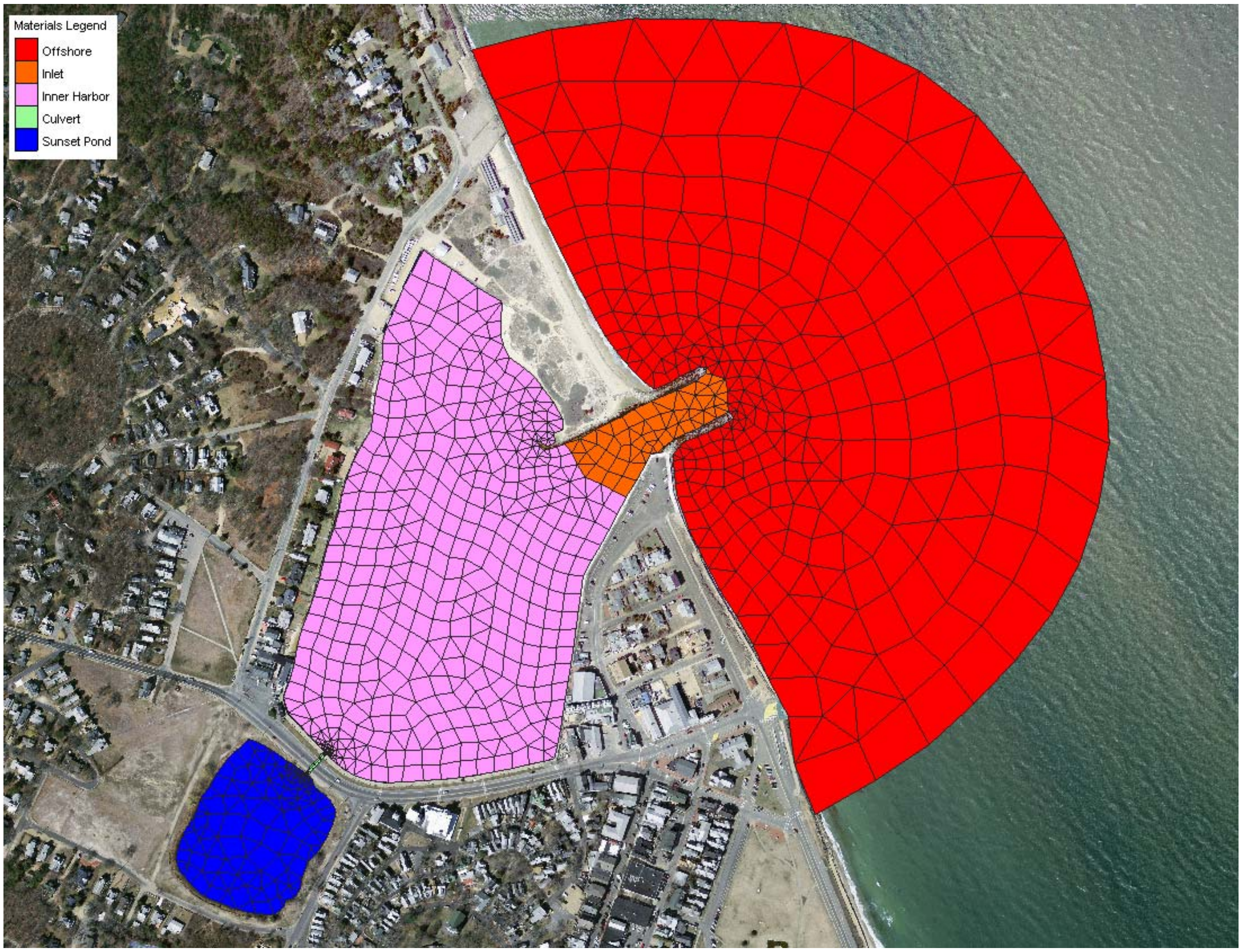


Figure V-9. Plot of hydrodynamic model grid mesh for Oak Bluffs Harbor. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

V.3.2.2 Boundary condition specification

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

Figure V-10. View of Sunset Lake box culvert to Oak Bluffs Harbor, from the pond side.

V.3.2.3 Calibration

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

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

Once visual agreement was achieved, a 7.5-day period (14 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section 2. The 7.5-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibration was performed for the period beginning March 29, 2012 at 18:00 (EDT).

After the model was calibrated, an additional verification run was made in order test the model performance in a time period outside of the calibration period. The model verification was performed for an eight-day period beginning April 13, 2012 at 5:00 (EDT).

The calibrated and verified model was used to analyze existing detailed flow patterns and compute residence times. The flushing analysis is based on the 15 day period beginning March 29, 2012 at 18:00 (EDT). The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire seven-day simulation. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events.

V.3.2.3.a Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient, and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.005 and 0.025 were specified for all element material types. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) (Henderson, 1966).

Table V-5. Manning's Roughness and eddy viscosity coefficients used in simulations of the Oak Bluffs Harbor and Sunset Lake Embayment System. These embayment delineations correspond to the material type areas shown in Figure V-11.

System Embayment	bottom friction	eddy viscosity lb-sec/ft^2
Nantucket Sound	0.025	40
Oak Bluffs Harbor Inlet	0.025	40
Oak Bluffs Harbor	0.025	20
Sunset Lake Culvert	0.005	20
Sunset Lake	0.010	20

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning's coefficients were matched to bottom type. For example, lower friction coefficients were specified for main basin of Oak Bluffs Harbor, versus Sunset Lake, which provides greater flow resistance. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based on ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992), and values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-5.

V.3.2.3.b Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Model turbulence coefficients were set between 20 and 40 lb-sec/ft^2 (Table V-5).

V.3.2.3.c Marsh porosity processes

Modeled hydrodynamics were complicated by wetting/drying cycles within Sunset Lake. Cyclically wet/dry areas of the fringing marsh areas of this embayment will tend to store waters as the tide begins to ebb and then slowly release water as the water level drops. This store-and-release characteristic of these marsh regions is typically responsible for the distortion of the tidal signal, and the elongation of the ebb phase of the tide. Because the marsh coverage along the perimeter of Sunset Lake is very small relative to the overall surface area of the basin, this tidal distortion effect is not observed in the tide data from any gauge deployed in the system.

Marsh porosity is a feature of the RMA-2 model that permits the modeling of hydrodynamics in marshes. This model feature essentially simulates the store-and-release capability of the marsh plain by allowing grid elements to transition gradually between wet and dry states. This technique allows RMA-2 to change the ability of an element to hold water, like squeezing a sponge.

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

A best-fit of model output for the measured data was achieved using the aforementioned values for friction and turbulent exchange. Figures V-11 through V-13 illustrate sections the 8-day simulation periods for the calibration model. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the system embayments. Four tidal constituents were selected for constituent comparison: the K_1, M_2, M_4 and M_6. Measured tidal constituent amplitudes are shown in Table V-6 for the calibration and verification simulations. The constituent amplitudes shown in this table differ from those in Table V-2 because constituents were computed for only the separate 8-day sub-sections of the 34-days represented in Table V-2. In Tables V-6 and V-7, error statistics are shown for the calibration and verification and the constituent amplitudes shown in these tables differ from each other because the each modeled run represent a different part of the time series.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The errors associated with tidal constituent amplitude for both the calibration and verification simulations were on the order of 0.001 ft, which is an order magnitude smaller than the accuracy of the tide gages (0.032 ft). Time lag errors for the main estuary reach were less than the time increment resolved by the model and tide data (10 minutes), indicating good agreement between the model and data. The skill of the model calibration is also demonstrated by the high degree of correlation (R^2) and low RMS error shown in Table V-8 for all stations.

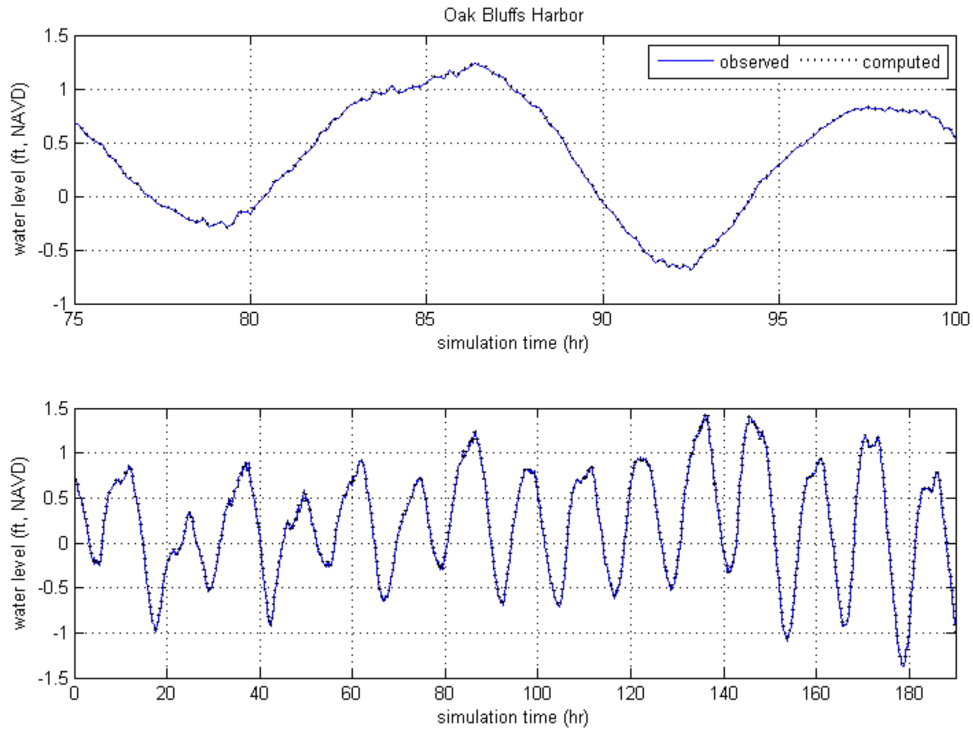


Figure V-11. Comparison of model output and measured tides for the TDR location offshore in Nantucket Sound (OBH-1) for the final calibration model run (March 29, 2012 at 18:00 EDT). The top plot is a 25-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

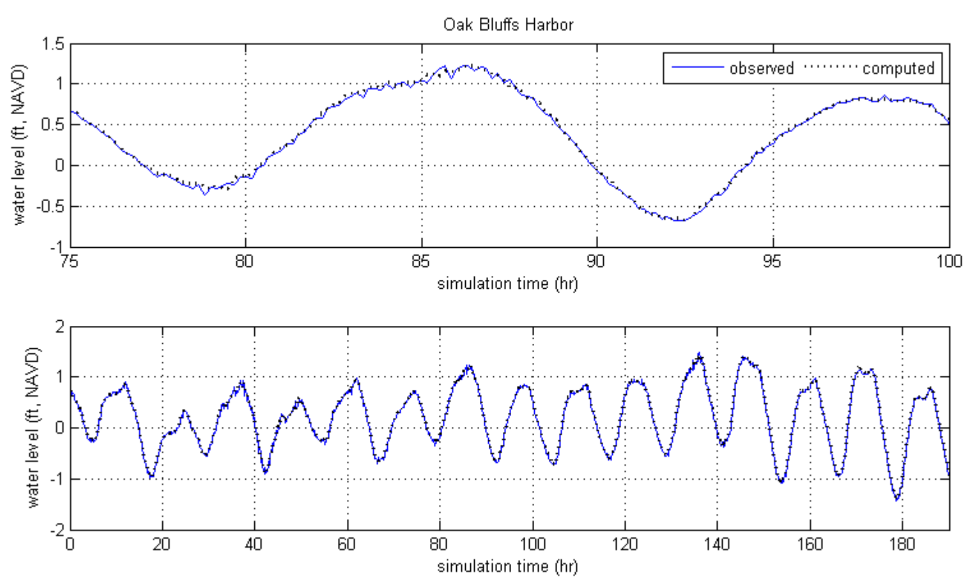


Figure V-12. Comparison of model output and measured tides for the TDR location in Oak Bluffs Harbor (OBH-2) for the final calibration model run (March 29, 2012 at 18:00 EDT). The top plot is a 25-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot

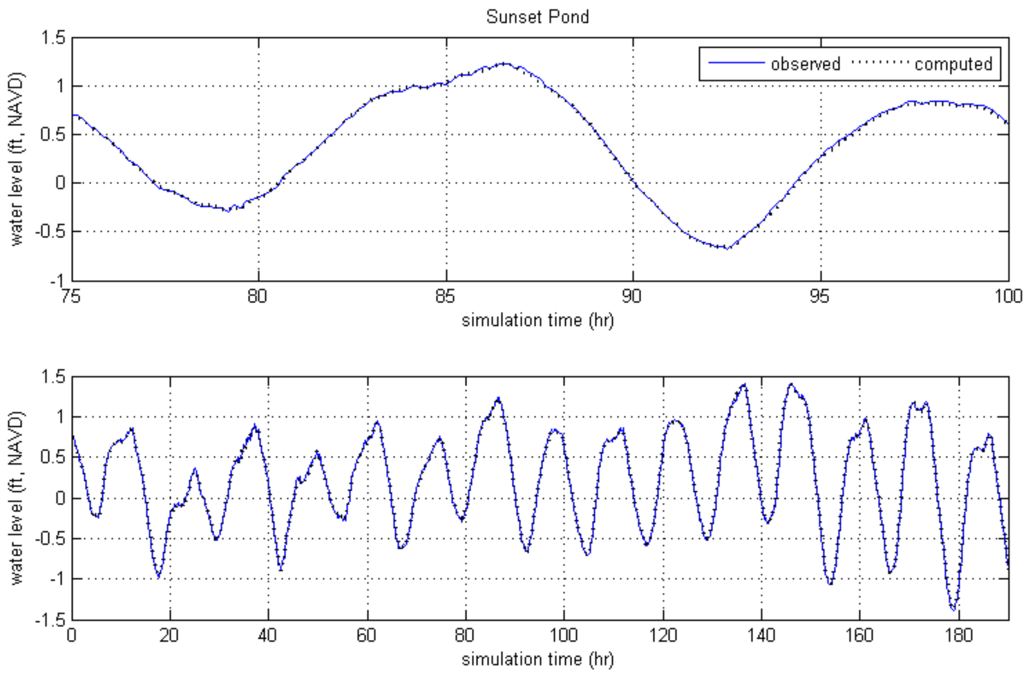


Figure V-13. Comparison of model output and measured tides for the TDR location in Sunset Lake (OBH-3) for the final calibration model run (March 29, 2012 at 18:00 EDT). The top plot is a 25-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

Table V-6. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for Oak Bluffs Harbor, during modeled calibration time period.

Model calibration run						
	Constituent Amplitude (ft)				Phase (deg)	
Location	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	0.756	0.154	0.052	0.078	33.056	99.948
Oak Bluffs Harbor	0.762	0.155	0.055	0.076	32.558	101.345
Sunset Lake	0.762	0.153	0.052	0.071	28.673	108.127
Measured tide during calibration period						
	Constituent Amplitude (ft)				Phase (deg)	
Location	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	0.756	0.154	0.052	0.078	33.125	99.831
Oak Bluffs Harbor	0.756	0.154	0.052	0.078	32.904	100.270
Sunset Lake	0.753	0.151	0.052	0.078	28.935	107.861
Error						
	Error Amplitude (ft)				Phase error (min)	
Location	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	0.000	0.000	0.000	0.000	0.142	0.121
Oak Bluffs Harbor	0.005	0.001	0.002	-0.002	0.717	1.113
Sunset Lake	0.009	0.002	0.000	-0.006	0.542	0.276

Table V-7. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for Oak Bluffs Harbor, during modeled verification time period.

Model verification run						
	Constituent Amplitude (ft)				Phase (deg)	
Location	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	0.732	0.157	0.063	0.116	27.039	-147.090
Oak Bluffs Harbor	0.739	0.157	0.066	0.114	27.553	-145.870
Sunset Lake	0.738	0.155	0.066	0.117	31.106	-138.730
Measured tide during verification period						
	Constituent Amplitude (ft)				Phase (deg)	
Location	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	0.731	0.157	0.063	0.116	26.981	-147.200
Oak Bluffs Harbor	0.732	0.157	0.063	0.116	27.211	-146.710
Sunset Lake	0.729	0.155	0.063	0.116	31.344	-138.400
Error						
	Error Amplitude (ft)				Phase error (min)	
Location	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	0.000	0.000	0.000	0.000	0.120	0.113
Oak Bluffs Harbor	0.007	0.000	0.003	-0.002	0.708	0.871
Sunset Lake	0.009	0.000	0.003	0.001	-0.492	-0.337

Table V-8. Error statistics for the Oak Bluffs Harbor hydrodynamic model, for model calibration and verification.

	Calibration		Verification	
Location	R^2	RMS error	R^2	RMS error
Nantucket Sound	1.00	0.00	1.00	0.00
Oak Bluffs Harbor	1.00	0.04	1.00	0.04
Sunset Lake	1.00	0.02	1.00	0.02

V.3.4 Model Circulation Characteristics

The final calibrated model serves as a useful tool in investigating the circulation characteristics of the Oak Bluffs Harbor and Sunset Lake Embayment System. Using model inputs of bathymetry and tide data, current velocities and flow rates can be determined at any point in the model domain. This is a very useful feature of a hydrodynamic model, where a limited amount of collected data can be expanded to determine the physical attributes of the system in areas where no physical data record exists. As an example, Figure V-14 shows color contours and vectors that indicate velocity during a single model time step, during a period of maximum flood currents at the inlet.

Figure V-14. Example of Oak Bluffs Harbor hydrodynamic model output for a single time step during a spring flood tide at the Oak Bluffs Harbor inlet. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

As another example, from the calibration model run of the Oak Bluffs Harbor and Sunset Lake Embayment System, the total flow rate of water flowing through the inlet culvert can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-15. During spring tides, the maximum flood flow rates approach 500 ft^3/sec at the Oak Bluffs Harbor Inlet.

Using the velocities computed in the model, an investigation of the flood or ebb dominance of different areas in the Oak Bluffs Harbor and Sunset Lake Embayment System can be performed. Marsh systems are typically flood dominant, meaning that maximum flood tide velocities are greater than during the ebb portion of the tide. Flood dominance indicates a tendency to collect and trap sediment, which is required to maintain healthy marsh resources.

Flood or ebb dominance in channels of a tidal system can be determined by performing a harmonic analysis of tidal currents. A discussion of the method of relative phase determination is presented in Friedrichs and Aubrey (1988). For this method, the M_2 and M_4 tidal constituents of a tidal velocity

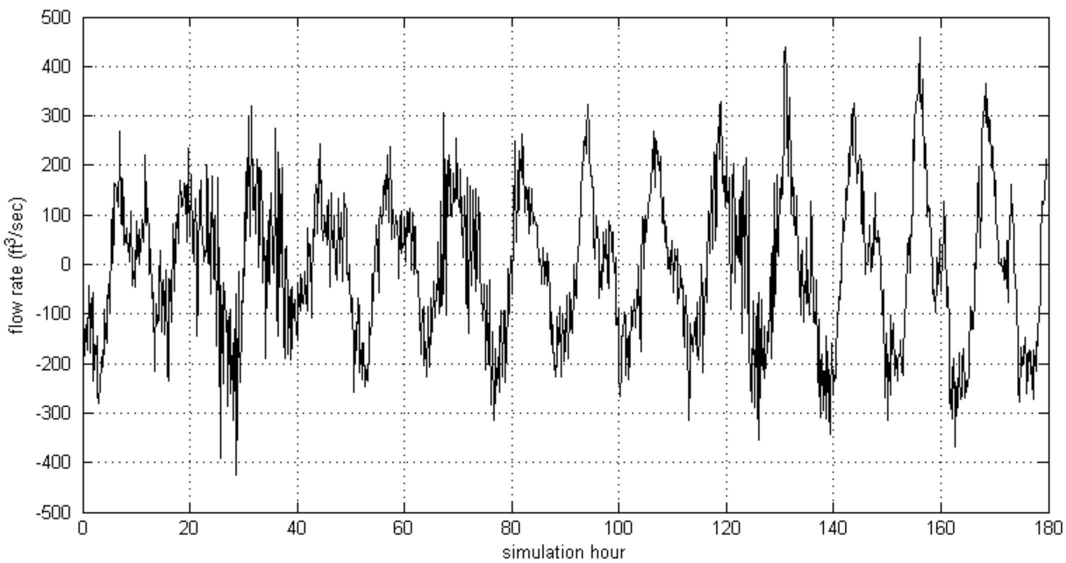


Figure V-15. Time variation of computed flow rates at the Oak Bluffs Harbor inlet. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flow indicated flooding tide flows, while negative flow indicates ebbing tide flows.

time series are computed, similar to the tidal elevation constituents presented in Section V.3.2.

The relative phase difference is computed as the difference between two times the M_2 phase and the phase of the M_4, expressed as $\Phi=2M_2-M_4$. If Φ is between 270 and 90 degrees ($-90<\Phi<90$), then the channel is characterized as being flood dominant, and peak flood velocities will be greater than for peak ebb. Alternately, if Φ were between 90 and 270 degrees ($90<\Phi<270$), then the channel would be ebb dominant. If Φ is exactly 90 or 270 degrees, neither flood nor ebb dominance occurs. For Φ equal to exactly 0 or 180 degrees, maximum tidal distortion occurs and the velocity residuals of a channel are greatest. This relative phase relationship is presented graphically in Figure V-16.

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

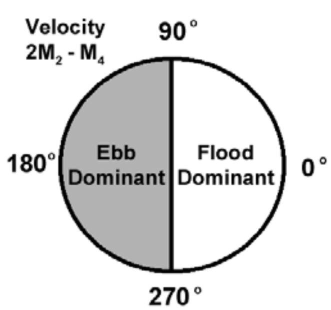


Figure V-16. Relative velocity phase relationship of M2 and M4 tidal velocity constituents and characteristic dominance, indicated on the unit circle. Relative phase is computed as the difference of two times the M2 phase and the M4 phase (2M2-M4). A relative phase of exactly 90 or 270 degrees indicates a symmetric tide, which is neither flood nor ebb dominant.

The computed values of $2M_2$-M_4 are presented in Table V-9. The results of this velocity analysis of the Oak Bluffs Harbor model output show that overall the system is neutral with slight ebb dominance. Ebb dominance is typical within Nantucket Sound as the water level is characterized by a “double peak” while flooding. Evidence of this may be seen in the decrease in slope of the observed water level at the offshore station during a flood tide in Figure V-5, indicating that an ebb dominated system is possible. During this “double tidal peak” flood currents decrease and sometimes reverse during a flood tide. Resultantly, higher ebb tide velocities are sustained for a longer period of time and erosion of the ebb dominated embayment occurs.

As indicated earlier ebb tidal dominance typically leads to a net loss of sediment from the embayment. However, current velocities within the Oak Bluffs Harbor and Sunset Lake Embayment System are small relative to many systems and the system only has slight ebb dominance. Therefore very little tidal driven erosion or accretion is likely in Oak Bluffs Harbor and Sunset Lake Embayment System because it is characterized by slow and mostly erosion neutral tidal currents. If ebb dominated areas within the system experience erosion, it is likely that only fine grained sediment will erode because currents velocities will be too low to move medium or coarse grained sediment; a process known as selective erosion.

Table V-9. Oak Bluffs Harbor relative velocity phase differences of M_2 and M_4 tide constituents, determines using velocity records.

Location	$2M_2$-M_4 relative phase (deg)	dominance
Oak Bluffs Harbor Inlet	100.3	weak ebb
Oak Bluffs Harbor	103.0	weak ebb
Sunset Lake	93.4	weak ebb

V.3.5 Flushing Characteristics

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

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

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

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

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using Sunset Lake as an example, the **system residence time** is the average time required for water to migrate from the pond, through Oak Bluffs Harbor, and into Nantucket Sound, where the **local residence time** is the average time required for water to migrate from Sunset Lake, into Oak Bluffs Harbor (not all the way to the Sound). Local residence times for each sub-embayment are computed as:

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

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

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

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

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

Residence times were calculated as the volume of water (based on the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Model divisions used to define the system sub-embayments include 1) the entire Oak Bluffs Harbor system, 2) Inner Oak Bluffs Harbor, 3) Sunset Lake. These system divisions follow the model material type areas designated in Figure V-11. Sub-embayment mean volumes and tide prisms are presented in Table V-10.

Table V-10. Embayment mean volumes and average tidal prism during simulation period for the Oak Bluffs Harbor and Sunset Lake Embayment System.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Oak Bluffs Harbor	11,328,000	3,162,000
Sunset Lake	440,000	352,000

Table V-11. Computed System and Local residence times for embayments in the Oak Bluffs Harbor and Sunset Lake Embayment System.

Embayment	System Residence Time (days)	Local Residence Time (days)
Oak Bluffs Harbor	1.9	1.9
Sunset Lake	16.7	0.6

The computed flushing rates for the harbor system show that as a whole, the system flushes well. A flushing time of 1.9 days for Oak Bluffs Harbor shows that on average, water is resident in the system for less than two days. Sunset Lake has the shortest local flushing time, because this embayment has a small mean sub-embayment volume, relative to its tide prism. This indicates that it flushes extremely well. The generally low local residence time in Sunset Lake indicates that it would likely have good water quality if the system water with which it exchanges (Oak Bluffs Harbor) also has good water quality. Actual water quality is still also dependent upon the total nutrient load to each embayment. For Sunset Lake, computed system residence times are on the order of 2 weeks (Table V-11), a magnitude much longer than its corresponding local residence time.

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

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

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort for the Oak Bluffs Harbor 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 Embayment

Extensive field measurements and hydrodynamic modeling of the embayment were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated model output representing the transport of water within the system embayment. Files of node locations and node connectivity for the RMA-2 model grid 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 output for the water quality model calibration was an 16-tidal cycle period in March and April 2012. 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 Embayment

Three primary nitrogen loads to an embayment 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 Oak Bluffs Harbor System, 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 Embayment

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 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 is the minimum required to provide a baseline for MEP analysis. Seven years of data (collected between 2001 and 2007) were available for stations monitored by SMAST in the Oak Bluffs Harbor System.

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 Oak Bluffs Harbor 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 the Oak Bluffs Harbor System. Like RMA-2 numerical code, RMA-4 is a two-dimensional depth averaged finite element model capable of simulating time-dependent

Table VI-1. Town of Oak Bluffs water quality monitoring data, and modeled Nitrogen concentrations for the Oak Bluffs Harbor System used in the model calibration plots of Figure VI-2. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means.

Sub-Embayment	Monitoring station	2001 mean	2002 mean	2003 mean	2004 mean	2005 mean	2006 mean	2007 mean	mean	s.d. all data	N	model min	model max	model average
Sunset Lake	MV-14	0.382	--	0.390	0.411	0.386	0.413	0.350	0.392	0.047	35	0.367	0.422	0.392
Oak Bluffs	MV-15	0.333	0.363	0.351	0.321	0.296	0.327	0.318	0.329	0.044	41	0.307	0.333	0.320
Oak Bluffs	MV-16	0.338	0.363	0.320	0.389	0.273	0.324	0.302	0.325	0.066	63	0.294	0.328	0.313
Oak Bluffs	MV-17	--	0.355	0.385	0.373	0.305	0.375	0.328	0.351	0.066	34	0.320	0.347	0.335

constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in numerous water quality studies of other embayments.

Figure VI-1. Estuarine water quality monitoring station locations in the Oak Bluffs Harbor System. Station labels correspond to those provided in Table VI-1.

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 SMAST and Martha's Vineyard Commission watershed loading analysis (based on the USGS watersheds), 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 system.

VI.2.1 Model Formulation

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

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

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

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

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

Based on groundwater recharge rates from the USGS, the hydrodynamic model was set-up to include ground water flowing into the system from the watersheds. Oak Bluffs Harbor has two watersheds contributing to the groundwater flow, the combined flow rate into the system is 0.50 ft^3/sec (1,218 m^3/day), and Sunset Lake watershed has a groundwater flow rate of 0.76 ft^3/sec (1,869 m^3/day).

For the 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 5 tidal-day (125 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 Oak Bluffs Harbor System.

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 direct atmospheric deposition load for Sunset Lake was evenly distributed across the grid cells that formed the embayment. Benthic regeneration load was 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 Oak Bluffs Harbor 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 coverage, 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 present conditions, the benthic flux is positive within Oak Bluffs Harbor and a negative benthic flux exists within Sunset Lake.

In addition to mass loading boundary conditions set within the model domain, a concentration along the model open boundary was specified. The model uses the specified concentration at the open boundary during the flooding tide periods of the model simulations. TN concentration of the incoming water is set at the value designated for the open boundary. The boundary concentration in Nantucket Sound was set at 0.235 mg/L, based on SMAST data from the Nantucket Sound (MV-12). The open boundary total nitrogen concentration represents long-term average summer concentrations found within Nantucket Sound.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Oak Bluffs Harbor System, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions.**

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Oak Bluffs Harbor	5.540	0.430	10.132
Sunset Lake	7.704	0.063	-4.283

VI.2.4 Model Calibration

Calibration of the total nitrogen model 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 Figure VI-2. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent areas of Oak Bluffs Harbor (Sunset Lake and the Harbor Basin) require values of *E* that are lower compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979). Observed values of *E* in these calmer 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 systems 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.

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for Oak Bluffs Harbor System.

Embayment Division	E m^2/sec
Offshore	2.6
Inlet	1.6
Inner Harbor	2.3
Culvert	2.2
Sunset Lake	1.4

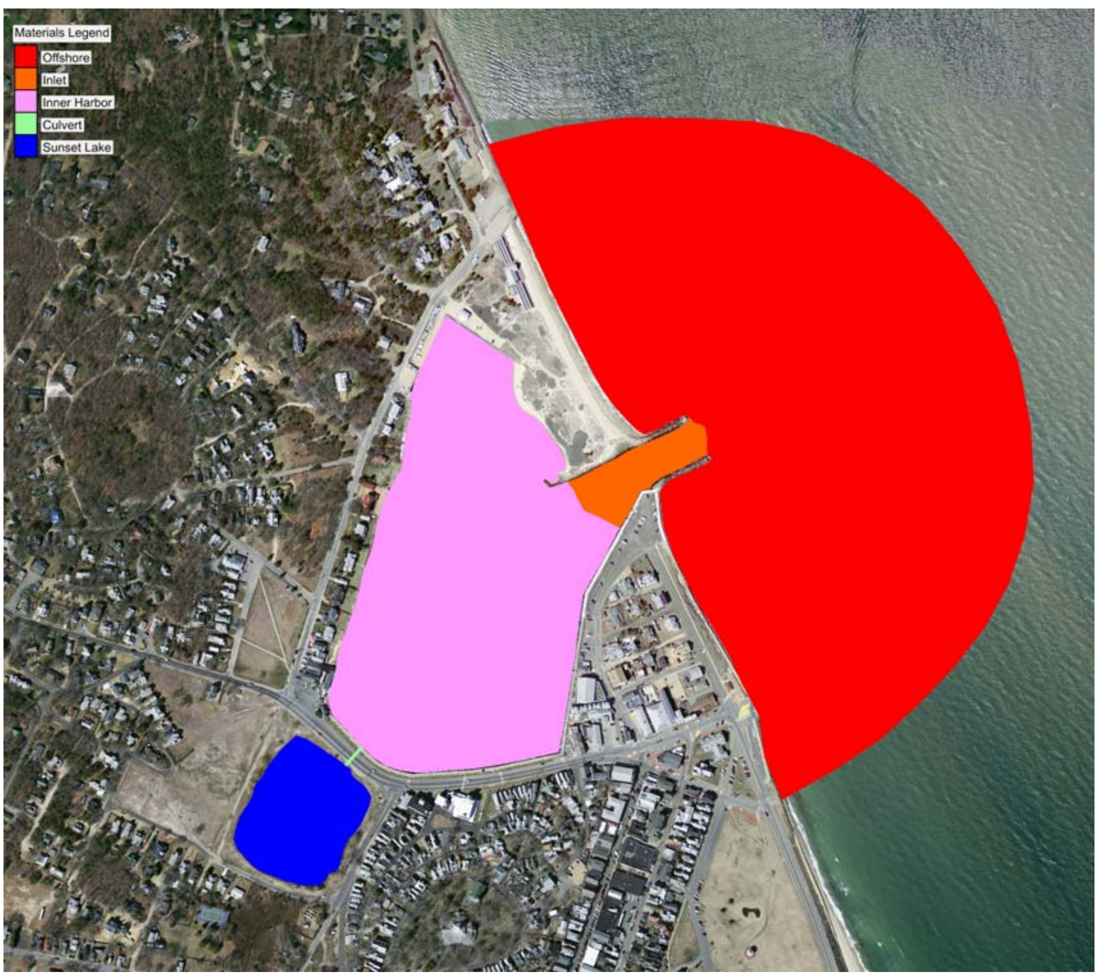


Figure VI-2. Map of Oak Bluffs Harbor water quality model longitudinal dispersion coefficients. Color patterns designate the different areas used to vary model dispersion coefficient values.

Comparisons between model output and measured nitrogen concentrations are shown in plots presented in Figure 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 SMAST 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 between the modeled mean and maximum TN because the monitoring data are collected, as a rule, during mid ebb tide.

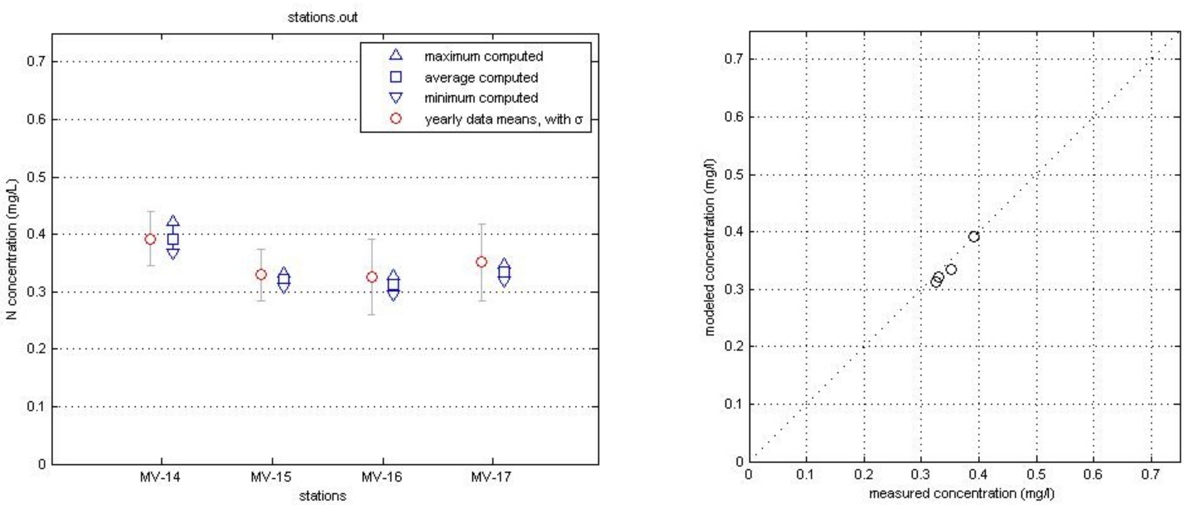


Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Oak Bluffs Harbor System. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed 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. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line.

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for the system. The model fit is exceptional for the Oak Bluffs Harbor System, with rms error of 0.01 mg/L and an R^2 correlation coefficient of 0.99.

A contour plot of calibrated model output is shown in Figure VI-4 for Oak Bluffs Harbor System. In the figure, color contours indicate nitrogen concentrations throughout the model domain. The output in the figure show average total nitrogen concentrations, computed using the full 5-tidal-day model simulation output period.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Oak Bluffs Harbor System using salinity data collected at the same stations as the nitrogen data. The only required inputs into the RMA4 salinity model of each 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 31.4 ppt. For groundwater inputs salinities were set at 0 ppt. The total groundwater input used for the model was 1.26 ft^3/sec (3,087 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed evenly within each watershed through grid cells that formed the perimeter along each watershed's land boundary.

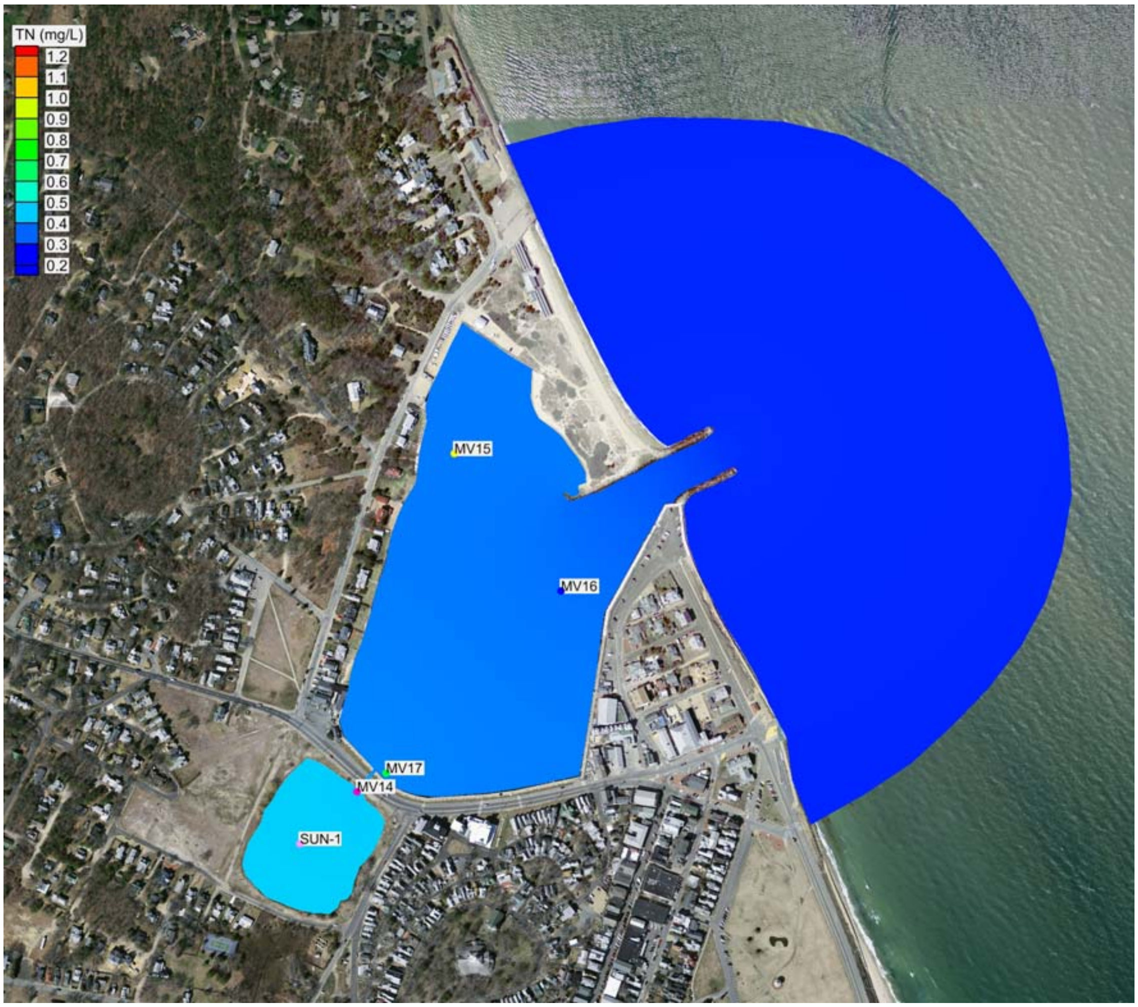


Figure VI-4. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for Oak Bluffs Harbor System. The approximate location of the sentinel threshold station for Oak Bluffs Harbor System (SUN-1) is shown.

Comparisons of modeled and measured salinities are presented in Figure VI-5, with contour plots of model output shown in Figure VI-6. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in Oak Bluffs Harbor System. The rms error of the models was 0.73 ppt, and correlation coefficient was 0.99. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical systems.

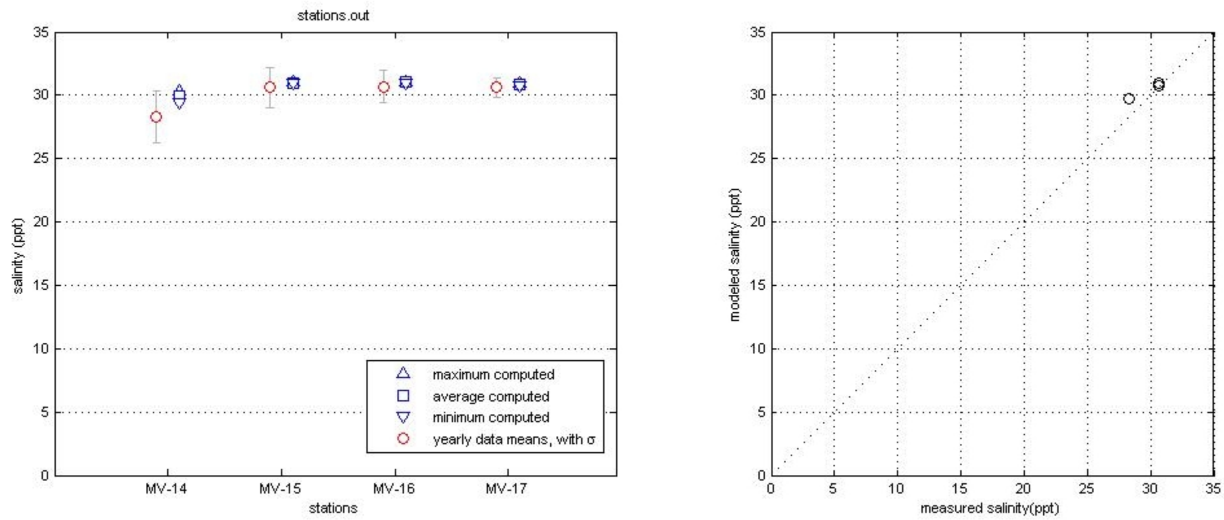


Figure VI-5. Comparison of measured and calibrated model output at stations in Oak Bluffs Harbor System. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (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. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the embayment system, two standard water quality modeling scenarios were run: 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.

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 Oak Bluffs Harbor 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
Oak Bluffs Harbor	5.540	6.386	+15.3%	0.477	-91.4%
Sunset Lake	7.704	9.849	+27.8%	0.148	-98.1%

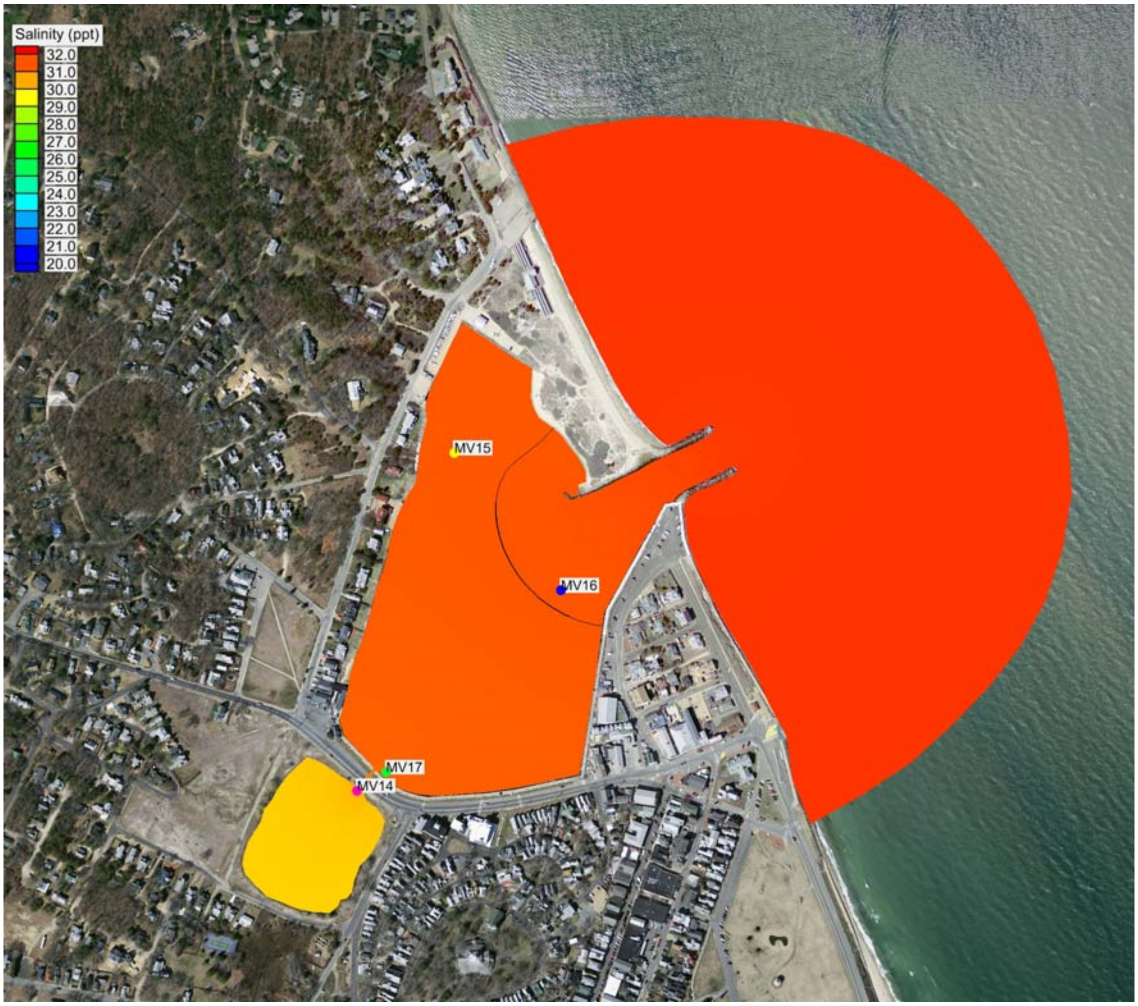


Figure VI-6. Contour plots of modeled salinity (ppt) in Oak Bluffs Harbor System.

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be a increase in watershed nitrogen load to the Oak Bluffs Harbor as a result of potential future development. Specific watershed areas would experience large load increases, for example the loads to Sunset Lake would increase 28% from the present day loading levels. For the no load scenarios, a majority of the load entering the watershed is removed; therefore, the load is significantly lower than existing conditions by over 98% overall.

For the build-out scenario, a breakdown of the total nitrogen load entering the Oak Bluffs Harbor System sub-embayments is shown in Table VI-5. 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 sub-embayment and surface water loads used for total nitrogen modeling of the Oak Bluffs Harbor 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)
Oak Bluffs Harbor	6.386	0.430	11.258
Sunset Lake	9.849	0.063	-5.479

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of Oak Bluffs Harbor System was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Vineyard Sound) remained identical to the existing conditions modeling scenarios. The stations in Oak Bluffs Harbor show steady increase in nitrogen from the inlet to the head of the system, with the largest increase within Sunset Lake. Color contours of model output for the build-out scenario are present in Figure VI-7. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-4, which allows direct comparison of nitrogen concentrations between loading scenarios.

Table VI-6. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Oak Bluffs Harbor System. Sentinel threshold station is in bold print.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Sunset Lake	MV-14	0.392	0.421	+7.6%
Oak Bluffs	MV-15	0.320	0.332	+3.8%
Oak Bluffs	MV-16	0.313	0.324	+3.6%
Oak Bluffs	MV-17	0.335	0.350	+4.5%
Sunset Lake	**SUN-1**	**0.408**	**0.442**	**+8.3%**

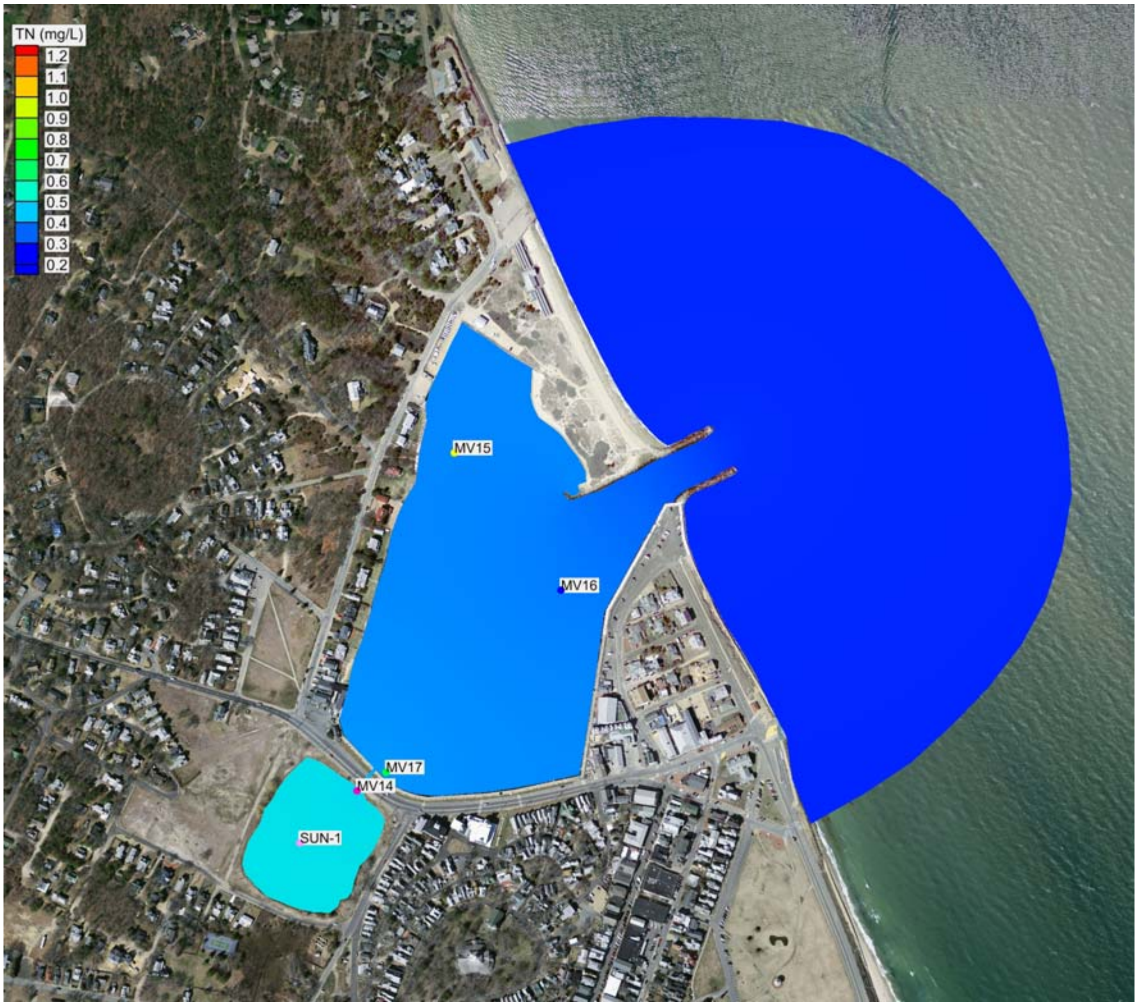


Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in Oak Bluffs Harbor System, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Oak Bluffs Harbor System (SUN-1) is shown.

VI.2.6.2 No Anthropogenic Load

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

Table VI-7. "No anthropogenic loading" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of Oak Bluffs Harbor 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)
Oak Bluffs Harbor	0.477	0.430	5.356
Sunset Lake	0.148	0.063	-0.082

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Again, total nitrogen concentrations in the receiving waters (i.e., Vineyard Sound) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was significant as shown in Table VI-8, with reductions ranging from 17% inside the inlet to Oak Bluffs with greater than 31% reduction in total nitrogen within Sunset Lake. Results for each system are shown pictorially in Figure VI-8.

Table VI-8. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the Oak Bluffs Harbor System. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). Sentinel threshold station is in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Sunset Lake	MV-14	0.392	0.269	-31.5%
Oak Bluffs	MV-15	0.320	0.263	-18.0%
Oak Bluffs	MV-16	0.313	0.260	-16.9%
Oak Bluffs	MV-17	0.335	0.266	-20.8%
Sunset Lake	**SUN-1**	**0.408**	**0.269**	**-34.1%**

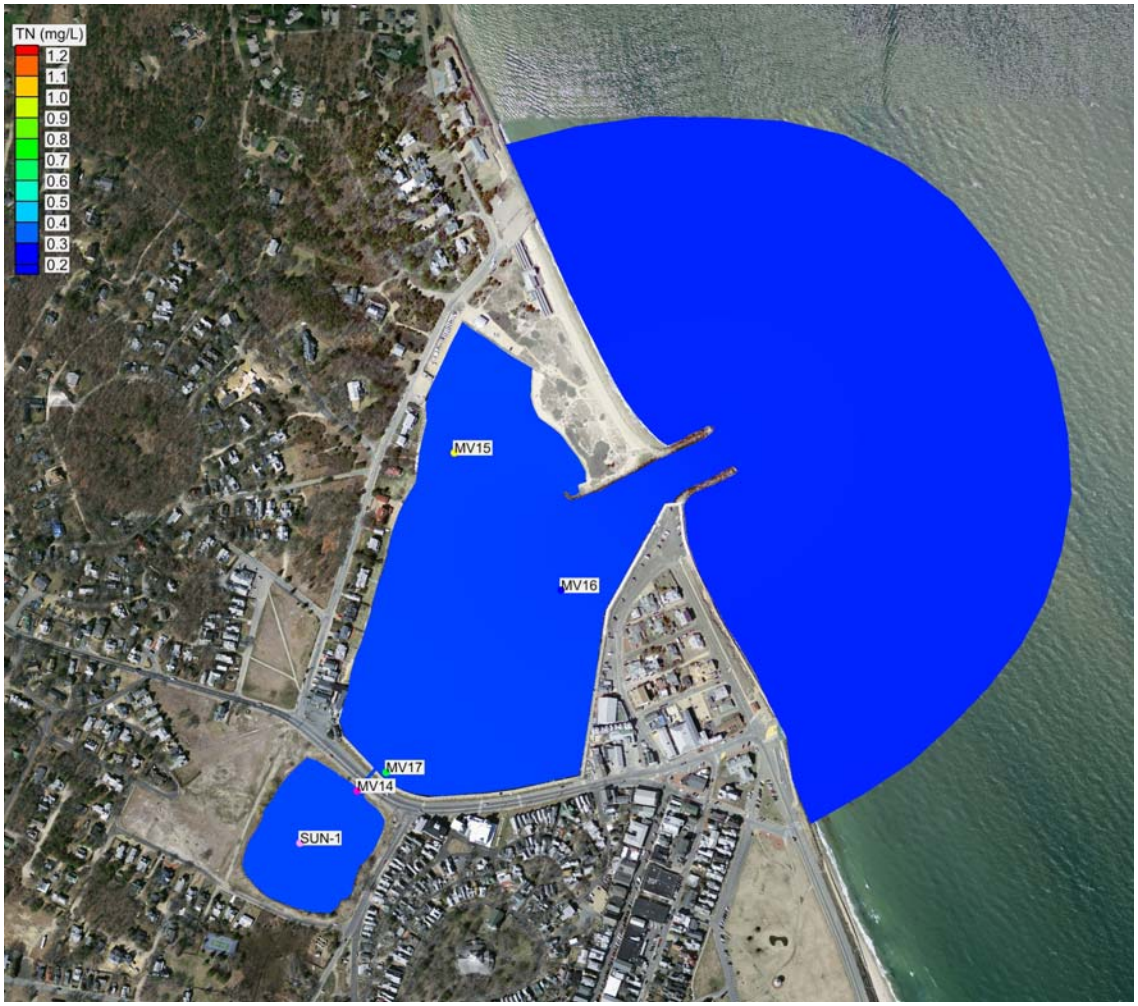


Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in Oak Bluffs Harbor System, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Oak Bluffs Harbor System (SUN-1) is shown.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll-*a*, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Oak Bluffs Harbor and Sunset Lake Embayment System, the MEP assessment is based upon data from the water quality monitoring program developed by the Town of Oak Bluffs and the Martha's Vineyard Commission, technical assistance from SMAST, as well as field survey and historical data collected under the programmatic umbrella of the Massachusetts Estuaries Project. These data include temporal surveys of eelgrass distribution; surveys of benthic animal communities and sediment characteristics; and time-series measurements of dissolved oxygen and Chlorophyll-*a* conducted during the summer and fall of 2006. These data form the basis of an assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for this system (Section VIII). Part of the MEP assessment necessarily includes confirmation that the critical nutrient for management in any embayment is nitrogen and determination that a system is or is not impaired by nitrogen enrichment. Analysis of inorganic N/P molar ratios within the watercolumn of the Oak Bluffs Harbor and Sunset Lake Embayment System support the contention that nitrogen is the nutrient to be managed, as the ratio in the Oak Bluffs Harbor main basin (~7) is well below the Redfield Ratio value (16) indicating that nitrogen additions will increase phytoplankton production, organic matter levels and turbidity within this system. Increased phytoplankton and organic matter levels increase oxygen consumption within the waters and sediments and increase the extent of oxygen depletion and habitat impairment. Values for Sunset Lake are less clear being near 16, suggesting that multiple factors (including nitrogen) may be in play in this small basin. This may be due to the large amount of watershed nitrogen entering this small basin. However, the overall data clearly indicate that for at least ~90% of the system, nitrogen is the nutrient of management focus. It should be noted that nitrogen enrichment occurs through two primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with the low nitrogen waters of Vineyard Sound. Oak Bluffs Harbor has seen increasing nitrogen loading from its watershed from shifting land-uses and is less affected from restricted tidal exchange. Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs, but this is less the case in Oak Bluffs Harbor which has a well maintained navigational channel.

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen threshold determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll-*a* (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed an autonomous dissolved oxygen sensor in Oak Bluffs Harbor at a location that would be representative of the dissolved oxygen condition within the main Harbor basin, on the southwestern side and slightly removed from the influence of inflowing waters from Vineyard Sound. The dissolved oxygen and Chlorophyll-*a* mooring was deployed to record the frequency and duration of low oxygen conditions and phytoplankton levels during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen overloading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Oak Bluffs Harbor system was conducted for comparison to historic records (MassDEP Eelgrass Mapping Program, C. Costello). The presence and 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. However, within the Oak Bluffs Harbor and Sunset Lake Embayment System, temporal changes in eelgrass distribution could not be established given the lack of eelgrass in the system as far back as 1951. While not all embayments are structurally capable of supporting eelgrass beds, the depth and water quality levels within Oak Bluffs Harbor in and of themselves do not appear to preclude eelgrass colonization.

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 (Sanders, H.L. 1960, Sanders, H.L. *et.al.*, 1980, Tian, Y.Q., J.J. Wang, J. A. Duff, B.L. Howes and A. Evgenidou. 2009) and New Bedford (Howes, B.L. and C.T. Taylor, 1990), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H’) and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 4 mg L^{-1}. Massachusetts State Water Quality Classification indicates that SA (high quality) waters be able to maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Oak Bluffs Harbor embayment are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality and that it is the designated water quality that is the target of TMDL's generated under the U.S. Clean Water Act. It is through the MEP and TMDL processes that site specific management targets are developed and under the Town's CWMP that management alternatives are designed and implemented to keep or bring the existing conditions in line with the Classification.

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

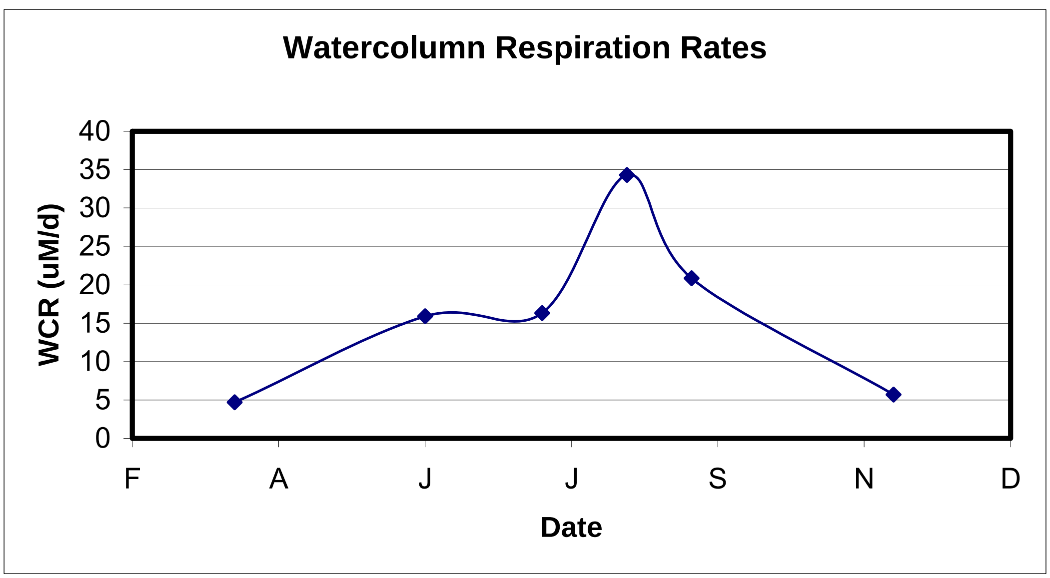


Figure VII-1. Example of typical average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System, Cape Cod (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter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

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

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

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

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate low-moderate nutrient enrichment of waters within the main basin of the Oak Bluffs Harbor System (Figures VII-3 through VII-4). The oxygen data are consistent with low organic matter enrichment from phytoplankton production as seen from the parallel measurements of chlorophyll-*a*. The measured levels of oxygen depletion and the relatively low chlorophyll-*a* levels follow the magnitude and spatial pattern of total nitrogen levels in this system (Section VI).

The oxygen record for Oak Bluffs Harbor shows that the main basin of the system has moderate daily oxygen excursions, indicative of low-moderate nitrogen enrichment. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The evidence of oxygen levels slightly above atmospheric equilibration indicates that the main basin of the system is slightly nitrogen enriched. However, in general, the daily excursions reach upper concentrations approximating atmospheric equilibrium with only a few significant higher excursions, consistent with low-moderate nitrogen enrichment. Note that high levels of nitrogen enrichment can result in phytoplankton blooms that generate D.O. levels routinely in the 10-12 mg L^{-1} range or higher at mid-day. The embayment specific results are as follows:

Oak Bluffs Harbor DO/CHLA Mooring (Figures VII-3 and VII-4):

The Oak Bluffs Harbor instrument mooring was located in the southwestern quadrant of the main basin of the Harbor (Figure VII-2). Moderate daily excursions in oxygen levels were observed at this location, generally ranging from air equilibration to 5 mg L^{-1} and infrequently to 4 mg L^{-1} (Figure VII-3, Table VII-1). Oxygen levels occasionally exceeded 8 mg L^{-1} and rarely exceeded 9 mg L^{-1}. These moderate oxygen levels are likely the result of the combined effects of low photosynthesis due to the low phytoplankton biomass and relatively well flushed water in the Harbor. The low organic enrichment of the system is demonstrated by the low rates of photosynthesis (seen in the air equilibration values) and the moderate declines in oxygen after sunset stemming from sediment and water column respiration.

Over the 48 day deployment there were no significant phytoplankton blooms. The beginning of the deployment period showed elevated levels of chlorophyll over a 2-3 day period, however, chlorophyll levels generally remained between 4-10 ug L^{-1}, averaging only 6 ug L^{-1} and exceeded the 10 ug L^{-1} benchmark only 2% of the time over the 2 month summer record (Table VII-2, Figure VII-4). The time-series record was consistent with the levels measured by the Water Quality Monitoring Program from 2001- 2007 where the Harbor Basin averaged 7 ug L^{-1} during summer months. Chlorophyll-*a* levels over 10 ug L^{-1} have been used to indicate moderate nitrogen enrichment in embayments. The levels in Oak Bluffs Harbor are relatively low for enclosed basins during summer.

The low-moderate levels of oxygen depletion and chlorophyll-*a* within the Oak Bluffs Harbor main basin indicate a system at or near its nitrogen assimilative capacity, the level of nitrogen enrichment the system can assimilate without habitat impairment. This assessment is consistent with the levels of total nitrogen and the oxygen and chlorophyll-*a* levels showing only moderate enrichment with the average long-term TN concentration for the basin of 0.34 mg N L^{-1} and for Sunset Lake 0.41 mg N L^{-1} (tidally averaged, Section VI).

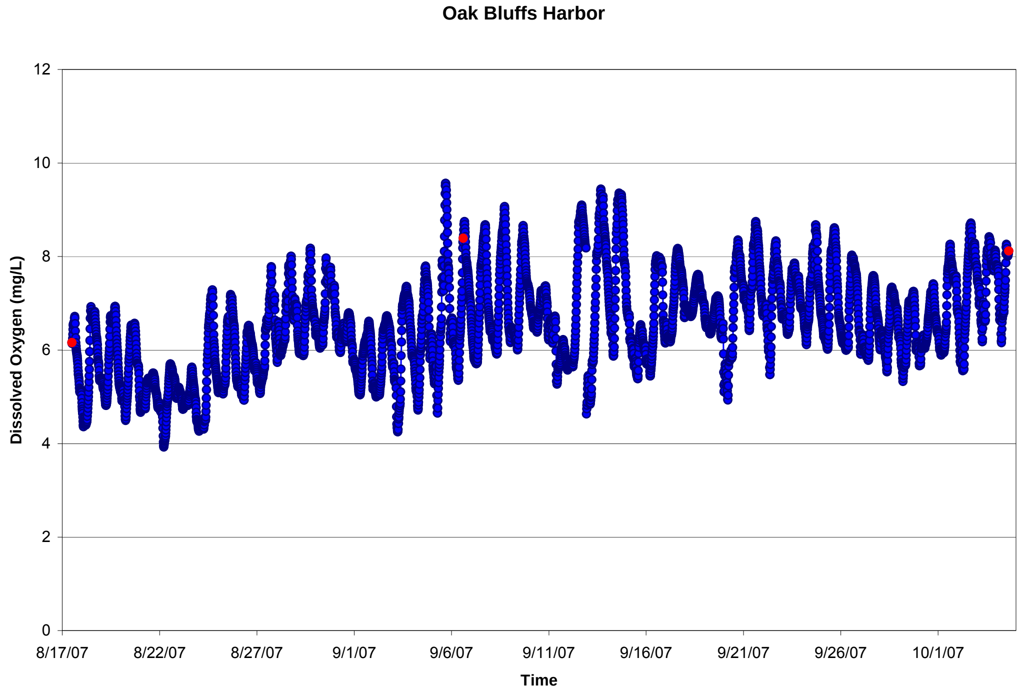


Figure VII-3. Bottom water record of dissolved oxygen at the Oak Bluffs Harbor station, Summer 2006. Calibration samples represented as red dots.

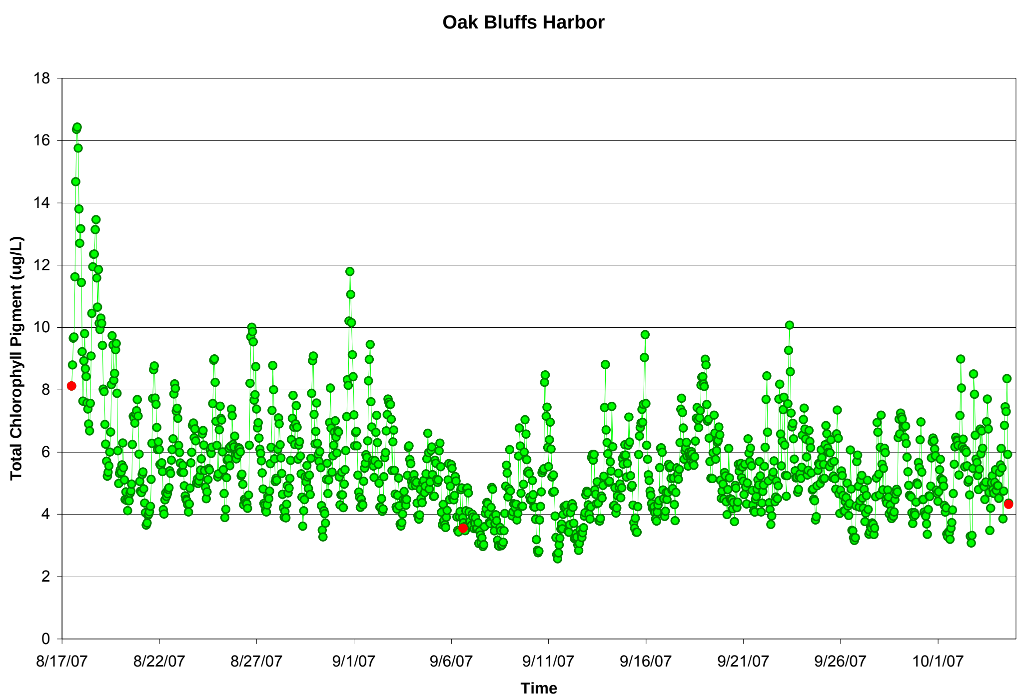


Figure VII-4. Bottom water record of Chlorophyll-*a* in the Oak Bluffs Harbor station, Summer 2006. Calibration samples represented as red dots.

Table VII-1. Days and percent of time during deployment of *in situ* sensors that bottom water oxygen levels were below various benchmark oxygen levels within the Oak Bluffs Harbor and Sunset Lake Embayment System.

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)
Oak Bluffs Harbor	**8/17/2007**	**10/4/2007**	**48.3**	**30%**	**7%**	**0.11%**	**NA**
			Mean	0.32	0.17	0.03	NA
			Min	0.01	0.01	0.01	NA
			Max	3.68	0.59	0.04	NA
			S.D.	0.56	0.18	0.02	N/A

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

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)
Oak Bluffs Harbor	**8/17/2007**	**10/4/2007**	**48.3**	**57%**	**2%**	**0%**	**0%**	**0%**
Mean Chl Value = 5.6 ug/L			**Mean**	0.32	0.19	0.13	NA	NA
			Min	0.04	0.04	0.13	0.00	0.00
			Max	2.42	0.42	0.13	0.00	0.00
			S.D.	0.40	0.17	N/A	N/A	N/A

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data is a key part of the MEP Approach. Surveys were conducted in the Oak Bluffs Harbor and Sunset Lake Embayment System by the DEP Eelgrass Mapping Program in 1995 and 2001 and integrated into the MEP effort, with additional observations during summer and fall 2006 by the SMAST/MEP Technical Team. The MassDEP surveys also included the near shore region of Vineyard Sound, to the north and south of the inlet into Oak Bluffs Harbor. The absence of eelgrass within Oak Bluffs Harbor as indicated in the 1995 and 2001 surveys was field validated by the MassDEP Eelgrass Mapping Program, as was the presence of the offshore beds. Historical analysis based upon available aerial photographs from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. The 1951 photo-interpretation data were validated through discussion with the Town of Oak Bluffs Shellfish Department. The primary use of the data is to indicate (a) estuarine regions that have historically or presently support eelgrass habitat, and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 (Figures VII-5); the period in which watershed nitrogen loading significantly increased to its present level. This temporal information can be used to determine the stability of the eelgrass community in many Southeastern Massachusetts embayments.

All of the available information on eelgrass relative to the man-made and heavily altered Oak Bluffs Harbor System indicates that this embayment has not supported eelgrass over the past half century and likely has not supported eelgrass for over the past century during which the system has been tidal. Oak Bluffs Harbor was originally a coastal pond, Lake Anthony (sometimes also called Meadow Pond), until it was opened to tidal flows and the inlet stabilized in the 1800's to create a marine harbor. The harbor continues to be maintained by dredging, with the main basin dredged in 1971-1972 and dredged again to remove shoaling in 2006. Dredging by the US Army Corps of Engineers is also planned for 2012. Even prior to recent activities, it is clear that this system never supported eelgrass.

It should be noted that while no eelgrass habitat could be documented within the Oak Bluffs Harbor and Sunset Lake Embayment System, the adjacent nearshore waters of Vineyard/Nantucket Sound does support eelgrass habitat (Figure VII-5). The acreage of eelgrass in these near shore Nantucket Sound waters appears to be relatively stable, although there does seem to be alteration of the bed configuration in relation to the tidal inlets to Oak Bluffs Harbor and Farm Pond to the south. It appears that the small losses may be due to recent marine activities, however, it is also possible that loss between the 1995 and 2001 surveys (<5%) is within the uncertainty of the data. It is not possible at this time to determine if this small change represents an anthropogenically driven decline, natural variation or sampling uncertainty at this site. Additional temporal sampling may be undertaken by the MassDEP Eelgrass Mapping Program to address this issue.

As eelgrass habitat could not be documented to exist, either historically or presently, within the Oak Bluffs Harbor and Sunset Lake Embayment System, the threshold analysis for this system is necessarily focused on restoration/protection of infaunal animal habitat. However, to the extent that nitrogen management of the Harbor is necessary it will also be protective of eelgrass and infaunal habitat within the down-gradient near shore waters of the Sound. This down-gradient effect, to the extent that it occurs, will be a by-product of any nitrogen management of the embayment, but is not part of the thresholds analyses for this system.

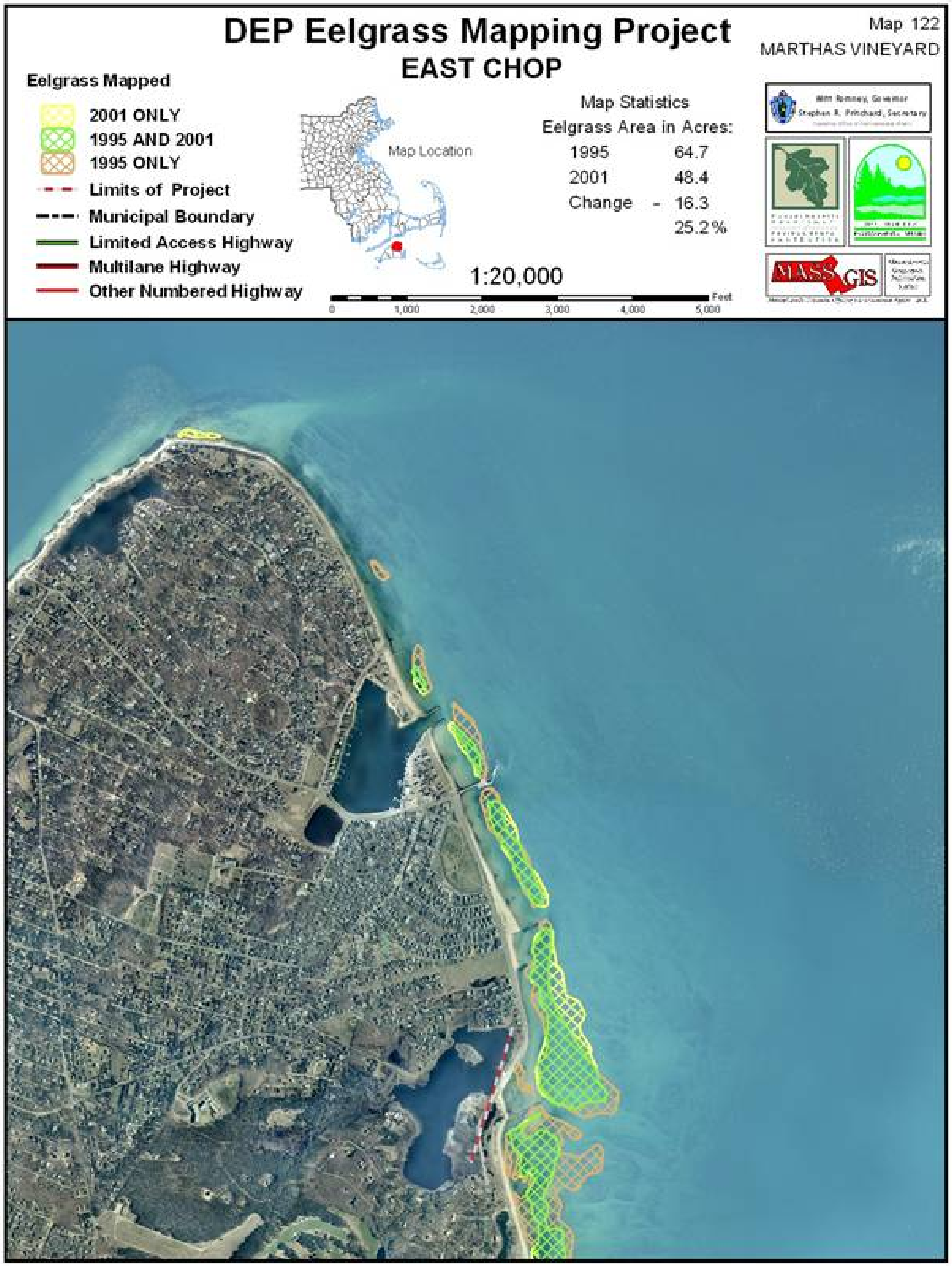


Figure VII-5. Eelgrass bed distribution within and offshore of the Oak Bluffs Embayment System. Beds delineated in 1995 are circumscribed by the brown outline, with 2001 outlined in yellow (map from the MassDEP Eelgrass Mapping Program). No eelgrass was found within Oak Bluffs Harbor in MassDEP surveys of 1995 and 2001 and the 1951 aerial survey, nor in the 2006 SMAST-MEP surveys. In contrast, offshore beds have been relatively stable over the study period. Note, Farm Pond eelgrass coverage is not shown in the figure.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 8 locations within the Oak Bluffs Harbor and Sunset Lake Embayment System (Figure VII-6), with replicate assays at each site. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that as there is no evidence of eelgrass ever colonizing Oak Bluffs Harbor or Sunset Lake, any nitrogen management of this embayment system should focus on benthic animal habitat. While Oak Bluffs Harbor may never support eelgrass beds given its role as an active harbor, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Section VIII).

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

Overall, the benthic infauna survey indicated that the main basin of Oak Bluffs Harbor is supporting a patchy distribution of high quality and impaired benthic habitat. The community consists of a moderate to low number of species and individuals, with a moderate to low diversity (0.75-2.1) and moderate Evenness (0.69). But organic enrichment indicator species (Capitellids, Tubificids) are not prevalent, comprising a minor fraction (<15%) of the population and species present and not indicative of nitrogen related stress. Bottom surveys by SCUBA divers indicated areas with bay scallops and dense populations of quahogs (*Mercenaria)*, large numbers of fish and shrimp. Equally important, the oxygen conditions, low Chlorophyll-*a* and total nitrogen levels (<0.335 mg N L^{-1}, tidally averaged) and high water turnover are inconsistent with a system impaired by nitrogen enrichment. While a detailed analysis of other factors that can also cause habitat impairment was not undertaken as part of this MEP analysis, there is evidence that disturbance of the bottom sedimentary habitat is likely playing a role in the main Harbor basin. The area of dredging activity conducted in May 2006 was confirmed through the Town of Oak Bluffs Shellfish Constable (personal communication, Mr. Dave Grunden). Dredging occurred ~ 5-months prior to the MEP infauna surveying activity and was limited to the area of the main navigational channel into the Harbor from the Harbormasters Office out the inlet channel. Dredging activity would not have affected areas of the 2006 MEP infaunal survey. More significant, however, appears to be disturbance of the sediments associated with the intense use of the Harbor as a marina and mooring area. Almost all of the central basin supports moorings and larger boats at low tide may cause some disturbance of unconsolidated surficial sediments. Other activities associated with an active harbor may also play some role. This conclusion is supported by the higher quality infauna habitat within Sunset Lake. This small (3 acre) basin has higher tidally averaged nitrogen levels than the main Harbor basin (0.41 mg N L^{-1} versus 0.32 mg N L^{-1}), yet supports communities with 26 species and >500 individuals, with high diversity (3.8) and Evenness (0.8), but supports no boat related activities (Table VII-3). It should be noted that some of the area along the southern reach of Sunset Lake was found to have drift algae accumulations causing patches of low quality benthic habitat. Patches of macroalgae that accumulate in areas along the southern shore of Sunset Lake can have a "smothering" effect on benthic animals as observed in the most extreme way in Waquoit Bay. However, as in the main Harbor basin, organic enrichment indicator species (Capitellids, Tubificids) were generally a small fraction of the community (<15%), consistent with the low Chlorophyll-*a* and moderate nitrogen levels, which do not indicate significant nitrogen related impairment. It should be noted that the patches of lower quality benthic habitat in Sunset Lake are associated with the patches of drift macroalgae and result in the conclusion that this basin is at or near its assimilative capacity for nitrogen inputs and is very near its nitrogen loading threshold. It is critical that the tidal exchange through the culvert to this small basin be maintained for proper management of this system.

Figure VII-6. Aerial photograph of the Oak Bluffs Harbor system showing location of benthic infaunal sampling stations (yellow symbols) within the main Harbor basin and Sunset Lake.

Local harbors that are of similar configuration to Oak Bluffs Harbor that show nitrogen enrichment (TN>0.6 mg N L^{-1}) and subsequent impairment of benthic habitats also typically have communities dominated by opportunistic indicator species, such as *Capitella capitata*. This stress indicator species is found in areas associated with hypoxia, chlorophyll rich basins and regions with high rates of organic matter deposition. Dominance by *Capitella* has been observed in high organic matter deposition areas, such as around the Hurricane Barrier and Palmers Island in New Bedford Harbor, a localized area of significant impairment. Capitellids and Tubificids (nitrogen/organic enrichment indicators) have also been documented as major portions of communities in one of the nitrogen enriched main basins of Allens Harbor (Harwich).

Table VII-3. Benthic infaunal community data for the Oak Bluffs Harbor and Sunset Lake Embayment System (inclusive of Sunset Lake). 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-6, (N) is the number of samples per site.

Basin	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)	Sta ID
Oak Bluffs Harbor Main Basin						
Main Basin	9	109	8	2.10	0.69	OBH-1.3.4
Northern Margin	2	14	--[1]	0.75	--[1]	OBH-8
Sunset Lake						
Main Basin	26	541	17	3.78	0.81	SL-1&2
Southern Shore	6	144	6	2.39	0.93	SL-3

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

Benthic infauna habitat within the main basin to Oak Bluffs Harbor is similar to that of Town Basin, which is the primary mooring and marina basin within Nantucket Harbor. In addition, it is similar to the boat basin area of Wild Harbor which is associated with the yacht club. The nitrogen and Chlorophyll-*a* levels of both the basins in Nantucket Harbor and Wild Harbor are similar to Oak Bluffs Harbor, indicative of high quality habitat, but the benthic animal community is showing some impairment not related to nitrogen enrichment.

The water quality parameters and heterogeneity of the benthic habitat quality and the presence of high quality benthic habitat within Sunset Lake at significantly higher levels of nitrogen enrichment are not consistent with a finding of impairment resulting from nitrogen enrichment for the main basin of Oak Bluffs Harbor. Instead, the benthic habitat in this basin is most likely the result of disturbance associated with an intensively used marine Harbor. This assessment underscores the need to use multiple nitrogen related habitat quality parameters, which need to yield consistent results before concluding nitrogen management is necessary for the restoration of an impaired estuarine habitat.

Other Benthic Resources:

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the propagation of shellfish (Figure VII-7). As is the case with some systems on Cape Cod, all of the enclosed waters of Oak Bluffs Harbor are classified as conditionally approved for the taking of shellfish during specific periods of the year, indicating the system is clearly impaired relative to the taking of shellfish. This relates to regulatory issues associated with marina activities and closures due to bacterial contamination. However, fecal coliform contamination does not generally result in ecological impacts, but is focused on public health concerns related with consumption of shellfish harvested from the Harbor and Sunset Lake basins. The primary impact of bacterial contamination is the closure of shellfish harvest areas, rather than the destruction of shellfish and other marine habitats. The seasonal shellfish closure of the Harbor and Lake is not due on-going measurement of bacteria levels, but rather is an administrative closure based solely on the intensity of boating activity in case of illicit or accidental boat discharges. Nevertheless, the Oak Bluffs Harbor system has also been classified as supportive of specific shellfish communities (Figure VII-8). The major shellfish species with potential habitat within the Oak Bluffs Harbor Estuary are soft shell clams (*Mya*) extending essentially along the shallow waters at the north and west edges of the harbor and quahogs (*Mercenaria*) throughout. In addition, the Oak Bluffs Harbor system has been designated as an area theoretically suitable for bay scallops and indeed some were observed during the collection by diver of sediment nutrient flux cores. Improving benthic animal habitat quality should also expand the shellfish growing area within this system.

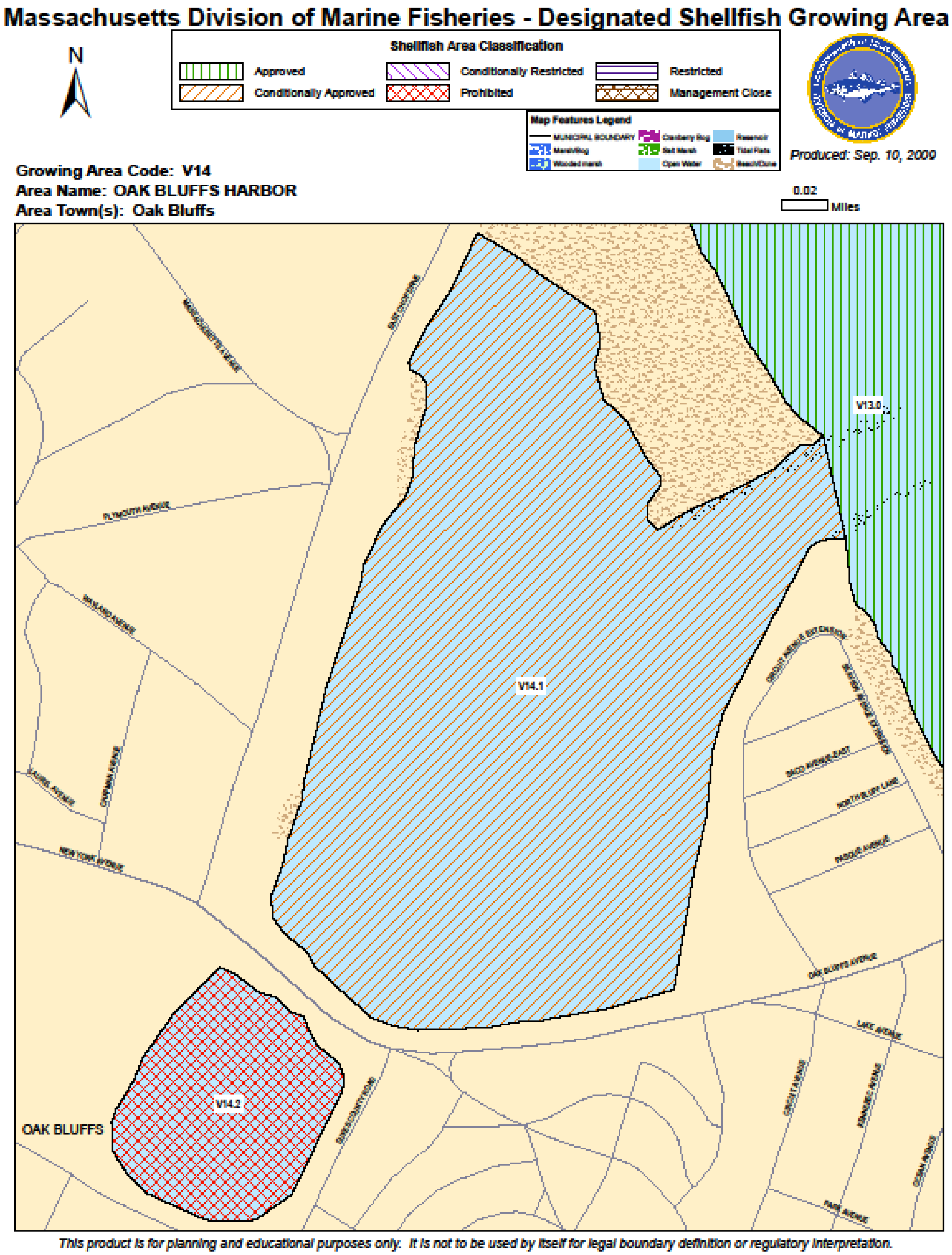


Figure VII-7. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

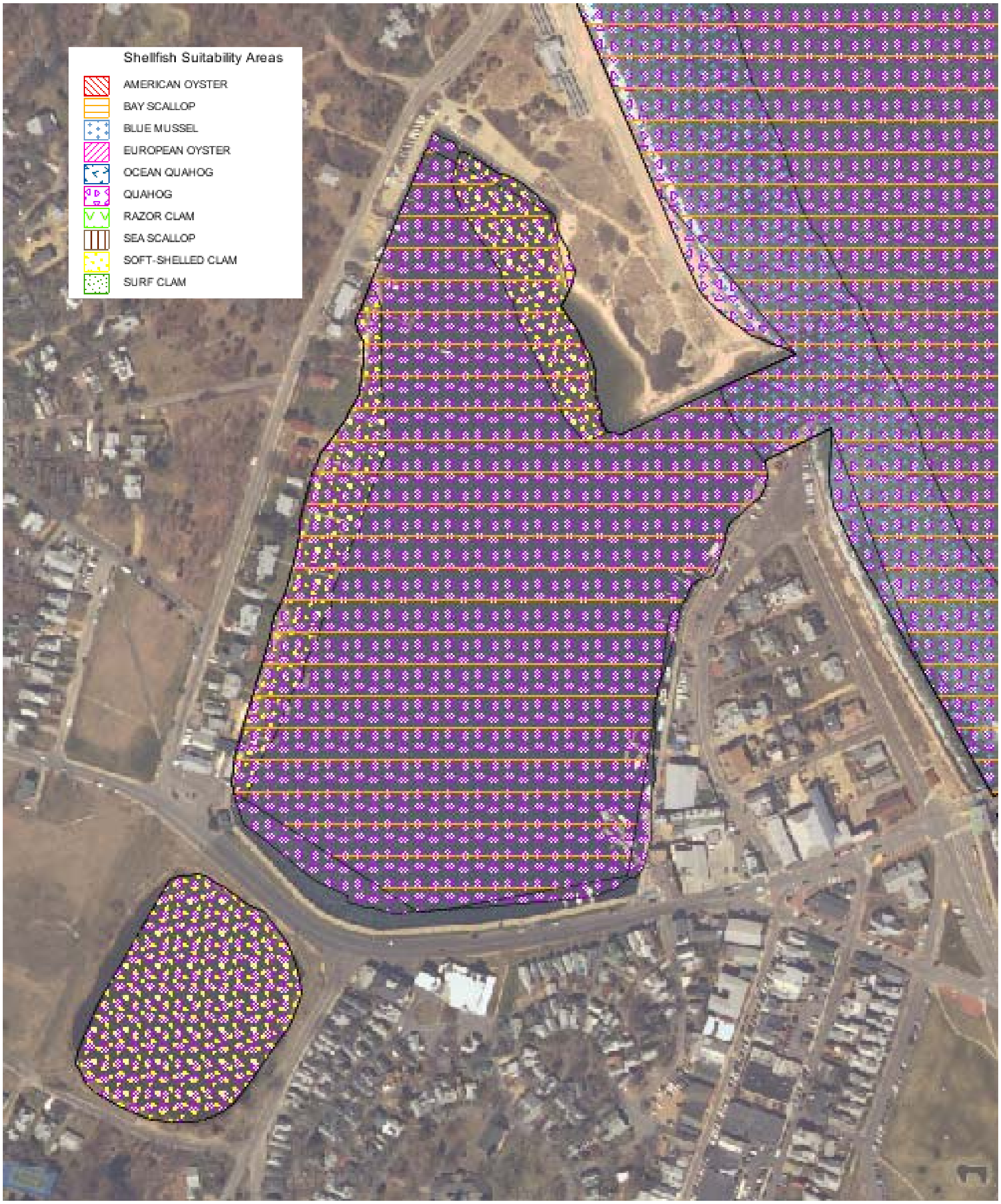


Figure VII-8. Location of shellfish suitability areas within the Oak Bluffs Harbor estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll). Additional information on temporal changes within each sub-embayment of an estuary, its associated watershed nitrogen load and geomorphological considerations such as basin depth, stratification and functional type further strengthen the analysis. These data were collected by the MEP to support threshold development for the Oak Bluffs Harbor Embayment System and were discussed in Section VII and summarized in Table VIII-1. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline Water Quality Monitoring Program conducted by the Town of Oak Bluffs and the Martha's Vineyard Commission with technical and analytical support from the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

The Oak Bluffs Harbor Embayment System is a man-made open water embayment significantly altered by human activity over the past approximately 100 years. Oak Bluffs Harbor was originally a coastal pond, Lake Anthony (sometimes also called Meadow Pond), until it was opened to tidal flows and the inlet stabilized in the 1800's to create a marine harbor. The harbor continues to be maintained by dredging, with the main basin dredged in 1971-1972 and dredging to remove shoaling in 2006. Dredging by the US Army Corps of Engineers is also planned for 2012. Due to the intensive use of the harbor shore for boat slips, ramps and other marine activities, there are no intertidal wetlands and the shoreline has been almost completely lined with hard coastal structures (e.g. bulkheads, riprap). Similarly, the small (3 acre) basin of Sunset Lake, separated from Oak Bluffs Harbor by a roadway, receives tidal flows through a small culvert. A small amount of fringing wetland is still present in this basin. These 2 component basins, once freshwater, form the Oak Bluffs Harbor Embayment System, which now functions as a tributary embayment to Nantucket/Vineyard Sound and must be managed as such.

All of the available information on eelgrass relative to the man-made and heavily altered Oak Bluffs Harbor System indicates that this embayment has not supported eelgrass over the past half century and likely has not supported eelgrass over the century that the system has been tidal. It should be noted that while no eelgrass habitat exists within the Oak Bluffs Harbor Embayment System, the adjacent nearshore waters of Vineyard/Nantucket Sound does support eelgrass habitat. The nearshore eelgrass within Nantucket/Vineyard Sound waters appears to be relatively stable, and the small decline between 1995 and 2001 is within the uncertainty of the data. As eelgrass habitat could not be documented to exist, either historically or presently, within the Oak Bluffs Harbor Embayment System, the threshold analysis for this system is necessarily focused on restoration/protection of infaunal animal habitat.

Within the Oak Bluffs Harbor main basin there were moderate daily excursions in oxygen levels, generally ranging from air equilibration to 5 mg L^{-1} and very infrequently to 4 mg L^{-1}. Oxygen levels occasionally exceeded 8 mg L^{-1} and rarely exceeded 9 mg L^{-1}. These moderate oxygen levels are likely the result of the combined effects of low photosynthesis due to the low phytoplankton biomass and the relatively well flushed water in the Harbor. The low organic enrichment of the system is demonstrated by the low rates of photosynthesis (seen in the air equilibration values) and the moderate declines in oxygen after sunset stemming from sediment and watercolumn respiration. The time series measurements in 2006 (48 days) found no significant phytoplankton blooms. Chlorophyll levels generally remained between 4-10 ug L^{-1}, averaging only 6 ug L^{-1} and exceeded the 10 ug L^{-1} benchmark only 2% of the time. The time-series record was consistent with the levels measured by the Water Quality Monitoring Program from 2001- 2007, where the Harbor Basin averaged 7 ug L^{-1} and Sunset Lake was similarly low with Chlorophyll-*a* levels, generally <10 ug L^{-1}, with no records >15 ug L^{-1} and summer time levels averaging 6 ug L^{-1} (2001-2007). These levels are only moderately higher than the offshore waters (3 ug L^{-1}). Chlorophyll-*a* levels over 10 ug L^{-1} have been used to indicate moderate nitrogen enrichment in embayments. The levels in Oak Bluffs Harbor are relatively low for enclosed temperate basins during summer. From the water quality data it would appear that the Oak Bluffs Harbor Embayment System is below its nitrogen assimilative capacity, the level of nitrogen enrichment a system can assimilate without habitat impairment. This assessment is consistent with the levels of total nitrogen and the oxygen and chlorophyll-*a* levels showing only moderate enrichment with the average long-term TN concentration for the basin of 0.34 mg N L^{-1} and for Sunset Lake 0.41 mg N L^{-1} (tidally averaged, Section VI).

Overall, the benthic infauna survey indicated that the main basin of Oak Bluffs Harbor is supporting a patchy distribution of high quality and impaired benthic habitat. The community consists of a moderate to low number of species and individuals, with a moderate to low diversity (0.75-2.1) and moderate Evenness (0.69). But organic enrichment indicator species (Capitellids, Tubificids) are not prevalent, comprising a minor fraction (<15%) of the population and species present not indicative of nitrogen related stress. Bottom surveys by SCUBA divers indicated areas with bay scallops and dense populations of quahogs (*Mercenaria)*, large numbers of fish and shrimp. Equally important, the oxygen conditions, low Chlorophyll-*a* and total nitrogen levels (<0.335 mg N L^{-1}, tidally averaged) and high water turnover are inconsistent with a system impaired by nitrogen enrichment. While a detailed analysis of other factors that can also cause habitat impairment was not undertaken as part of this MEP analysis, there is evidence that disturbance of the bottom sedimentary habitat is likely playing a role in the main Harbor basin. The area of dredging activity conducted in May 2006 was confirmed through the Town of Oak Bluffs Shellfish Constable (personal communication, Mr. Dave Grunden). Dredging occurred ~ 5-months prior to the MEP infauna surveying activity and was limited to the area of the main navigational channel into the Harbor from the Harbormasters Office out the inlet channel. Dredging activity would not have affected areas of the 2006 MEP infaunal survey. More significant, however, appears to be disturbance of the sediments associated with the intense use of the Harbor as a marina and mooring area. Almost all of the central basin supports moorings and larger boats at low tide may cause some disturbance of unconsolidated surficial sediments, while the shoreline is nearly completely ringed with boat slips, docks, piers, ramps and other marine structures. Other activities associated with an active harbor may also play some role. This conclusion is supported by the higher quality infauna habitat within Sunset Lake. This small 3 acre basin, has higher tidally averaged nitrogen levels than the main Harbor basin (0.41 mg N L^{-1} versus 0.32 mg N L^{-1}), yet supports communities with 26 species and >500 individuals, with high diversity (3.8) and Evenness (0.8), but supports no boat related activities (Table VII-5), although some of the area along the southern reach of Sunset Lake was found to have drift algae accumulations causing patches of low quality benthic habitat. The benthic animal communities in the basin of Sunset Lake are comparable to high quality environments, such as the Outer Basin of Quissett Harbor The Outer Basin of Quissett Harbor supports benthic animal communities with $\geq$28 species, >400 individuals with high diversity (H' $\geq$3.7) and Evenness (E $\geq$0.77). Similarly, outer stations within Lewis Bay in Barnstable currently support similarly high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Evenness (0.74). Equally important, these communities are not consistent with nutrient enrichment being composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms. Yet the main basin of Oak Bluffs Harbor, with its lower total nitrogen and Chlorophyll-*a* levels and generally good oxygen levels, has only low-moderate numbers of species and individuals forming a community of low - moderate diversity and Evenness. Equally important, unlike Sunset Lake, the main Harbor basin has only a small fraction of the benthic animal community (<15%) and was composed of organic enrichment indicator species (Capitellids, Tubificids), consistent with the low Chlorophyll-*a* and moderate nitrogen levels. Furthermore, surveys by SCUBA diver observed a patchy environment with areas with active fauna (bay scallops, quahogs, dense worm burrows, fish, shrimp, etc.) and areas of disturbed sediments.

If the cause of the impaired benthic habitat were nitrogen enrichment then at the higher nitrogen levels observed in Sunset Lake the habitat should be worse, but it is generally better than the main Harbor basin. Similarly, there should be relatively consistent habitat quality at similar depths within the main Harbor basin not patches of high quality habitat (e.g. bay scallops) and there should be higher total nitrogen levels as the levels in Oak Bluffs Harbor are equal to or lower than high quality embayment basins throughout the region most notably, Nantucket Harbor. The nitrogen and Chlorophyll-*a* levels within Oak Bluffs Harbor are indicative of high quality habitat.

Based upon integrating all of the metrics and supporting information (water quality parameters, heterogeneity of the benthic habitat quality and presence of high quality benthic habitat within Sunset Lake at significantly higher levels of nitrogen enrichment) it must be concluded that while the benthic animal habitat within the main Harbor basin is impaired, the impairment cannot be attributed to nitrogen enrichment. Instead, at this time it appears that the benthic habitat impairment is most likely the result of disturbance associated with an intensively used marine Harbor. This assessment underscores the need to use multiple nitrogen related habitat quality parameters, which need to yield consistent results before concluding nitrogen management is necessary for the restoration of an impaired estuarine habitat.

Classification of habitat quality necessarily included the structure of the estuarine basin, specifically that it is fully representative of a tidal embayment, as opposed to a tidal river or salt marsh basin. Integration of all of the metrics clearly indicates that the basin of Oak Bluffs Harbor is not impaired by nitrogen enrichment, but that Sunset Lake, while generally supporting good benthic animal habitat, does have areas associated with drift macroalgae and are moderately impaired. Total nitrogen (TN) levels within Sunset Lake (0.41 mg N L^{-1}, tidally averaged) are relatively low compared to the more than 60 estuaries assessed by the MEP where benthic animal habitat impairment is generally not observed at TN levels <0.5 mg N L^{-1}. However, due to the patches of lower quality benthic habitat in Sunset Lake associated with patches of drift macroalgae it appears that this basin is currently at or near its assimilative capacity for nitrogen inputs, hence is very near its nitrogen loading threshold. It is critical that the tidal exchange through the culvert to this small basin be maintained for proper management of this system.

Table VIII-1. Summary of **Nitrogen Related Habitat Health** within the Oak Bluffs Harbor Embayment System, Town of Oak Bluffs, Martha's Vineyard, MA, based upon assessment data (Section VII). The estuary is presently functioning primarily as an open water embayment comprised of a down-gradient main basin and an up-gradient enclosed tributary basin, typical of coastal embayments throughout southeastern Massachusetts. **Note that ranking relates only to nitrogen related impairments, not other disturbances.**

	Oak Bluffs Harbor Embayment System	
Health Indicator	**Oak Bluffs Harbor Main Basin**	**Sunset Lake**
Dissolved Oxygen	H-MI[1]	--[2]
Chlorophyll	H[3]	H[4]
Macroalgae	H-MI[5]	H-MI[6]
Eelgrass	--[7]	--[7]
Infaunal Animals	H-MI[8]	H-MI[9]
Overall:	**H[10]**	**H-MI[11]**

1 – oxygen levels generally >5 mg/L (93% record), WQMP sampling only 1% of samples <5 mg/L, 86% of samples >6 mg/L with periodic depletions 4-3 mg/L; sediments have oxidized surface

2 – oxygen not sampled in Sunset Lake, but not evidence of low oxygen conditions; sediments oxidized except under patches of drift algae.

3 – low Chlorophyll-*a* levels, generally <10 ug/L, time-series average= 6 ug/L, WQMP (2001-2007) basin average= 7 ug/L, <10 ug/L 71% of samples, always <20 ug/L, offshore average = 3ug/L

4 – low Chlorophyll-*a* levels, generally <10 ug/L, WQMP (2001-07) basin average= 6 ug/L, <10 ug/L 86% of samples, always <15 ug/L, offshore average = 3ug/L

5 – patchy accumulations of drift red algae, possibly *Gracillaria*.

6 – patchy accumulation of drift algae along southern shore, primarily *Ulva*.

7 – no evidence this basin has been historically supportive of eelgrass, and no eelgrass in MassDEP (C. Costello) assessments of 1951, 1995, 2001 or SMAST-MEP 2006 survey.

8 – moderate-low species numbers & number of individuals. Moderate-Low diversity (0.75-2.1) & Evenness (0.69). But organic enrichment indicator species (Capitellids, Tubificids) <15% of population and species present not indicative of nitrogen related stress. Some areas with bay scallops and *Mercenaria*, large numbers of fish, shrimp. Low numbers associated with disturbance in mooring area and patches of drift macroalgae. Disturbed sediments in much of basin.

9 – moderate numbers of species and high number individuals. High diversity & Evenness; variable habitat with crustaceans, polychages and mollusks dominating some areas. Low species numbers dominated by polychaetes and crustaceans associated with drift macroalgae. Low numbers (<15%) of organic enrichment indicator species (Capitellids, Tubificids) does not indicate N related impairment.

10 – No evidence of Nitrogen Related Impairment: Oxygen levels show only brief moderate depletions, chlorophyll and total nitrogen levels are low. Benthic habitat with low numbers of organic enrichment species and bay scallops observed as well as patches of intense bioturbation. But habitat is patchy with most areas showing oxidized sediments except in recent dredged areas (2006) or associated with drift macroalgal accumulations. Sediments are disturbed in many areas by moorings and apparent boating activities. At higher levels of nitrogen in Sunset Lake which is not a marina, benthic communities showed higher habitat quality. Benthic habitat is patchy with impaired areas, but does not appear related to nitrogen enrichment. No history of eelgrass habitat in this basin.

11 – No evidence of Nitrogen Related Impairment: Chlorophyll and total nitrogen levels are low. Benthic habitat with low numbers of organic enrichment species. Much of the basin has high numbers of species and individuals, although along the southern shore there are patches of drift macroalgae that reduce species numbers. No history of eelgrass habitat in this basin.

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 protecting against impairment of benthic animal communities related to nitrogen enrichment within the Oak Bluffs Harbor Embayment System is based primarily upon the nutrient and oxygen levels and current benthic community indicators, as there is no history of eelgrass colonization of this system. 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.

Based upon the assessment in Section VII and in the above Section VIII-1, it appears that benthic animal habitat within the Harbor basin is impaired but that the impairment is inconsistent with nitrogen enrichment. Within Sunset Lake (3 acres), while the main basin supports high quality habitat, the southern region has patches of drift macroalgae (*Ulva*) which is causing some impairment of habitat suggesting that this portion of the system is at or near its threshold (i.e. the level of nitrogen a system can tolerate without impairment) under present nitrogen loading rates and tidal flushing conditions. The general absence of nitrogen related habitat impairment is consistent with oxygen and Chlorophyll-*a* levels and parallels the gradient in watercolumn total nitrogen levels within this estuary, with higher TN levels within the upper Sunset Lake basin, where much of the watershed load enters.

The sentinel station for the Oak Bluffs Harbor Embayment System was established within the mid basin of Sunset Lake and nitrogen threshold target developed to prevent nitrogen related degradation of benthic animal habitat throughout the system. As there was not a long-term water quality monitoring station within Sunset Lake, the water quality model was used to determine the present tidally averaged total nitrogen level under present loading conditions at mid-basin, in order to refine nitrogen threshold development (Section VI). Using this approach, the tidally averaged total nitrogen level at the sentinel station is presently 0.41 mg TN L^{-1}. This TN levels is comparable to other estuarine basins throughout the region that show similar water quality, organic enrichment and unimpaired benthic animal habitat. In numerous estuaries it has been previously determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat (e.g. Eel Pond, Parkers River, upper Bass River, upper Great Pond, upper Three Bays, Rands Harbor and Fiddlers Cove). However, it appears that Sunset Lake is presently near its threshold, so a threshold level of 0.45 mg TN L^{-1} is more appropriate to be protective of this apparently nitrogen sensitive basin. The slightly lower threshold for Sunset Lake compared to the much larger semi-enclosed basins noted, is consistent with its enclosed structure and that it receives the bulk of the watershed nitrogen loading (in plant available forms) to the embayment system. As the threshold nitrogen level is higher than present conditions watershed management should focus on keeping future build-out nitrogen loads below levels that would result in nitrogen levels at the sentinel station from exceeding the threshold (Section VIII.3). Nitrogen management to lower watershed loading to Oak Bluffs Harbor is not indicated under the watershed loads extant at the time of this assessment.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were in turn used to determine the amount of total nitrogen mass loading increase that could be accommodated within Sunset Lake without inhibiting benthic animal habitat in Sunset Lake and the overall Oak Bluffs Harbor 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 from the Build-Out Scenario (Section VI.2.6.1) were sequentially increased until the nitrogen levels reached the threshold level at the sentinel stations chosen for the Oak Bluffs Harbor System (SUN-1 is located approximately at the center of Sunset Lake). The load increases presented below represent only one of a suite of potential approaches. Community discussions should review this option and consider evaluation of other alternatives. The presentation below is to establish the general degree and spatial pattern of loading that can potential be tolerated without significant impairment of the benthic animal habitat of the System.

As shown in Table VIII-2, the nitrogen load increase within the system necessary to achieve the threshold nitrogen concentration allowed for the addition of 100 kg/year of nitrogen to the Sunset Lake watershed in addition to the load increases specified within the Build-Out Scenario. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the Oak Bluffs Harbor 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
Oak Bluffs Harbor	4.307	5.153	+19.7%
Sunset Lake	7.036	9.455	+34.4%

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 increased Nitrogen load depicted in Table VIII-2. The Build-Out Scenario load with the addition of 100 kg/yr results in the total nitrogen loads presented in Table VIII-4. 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.

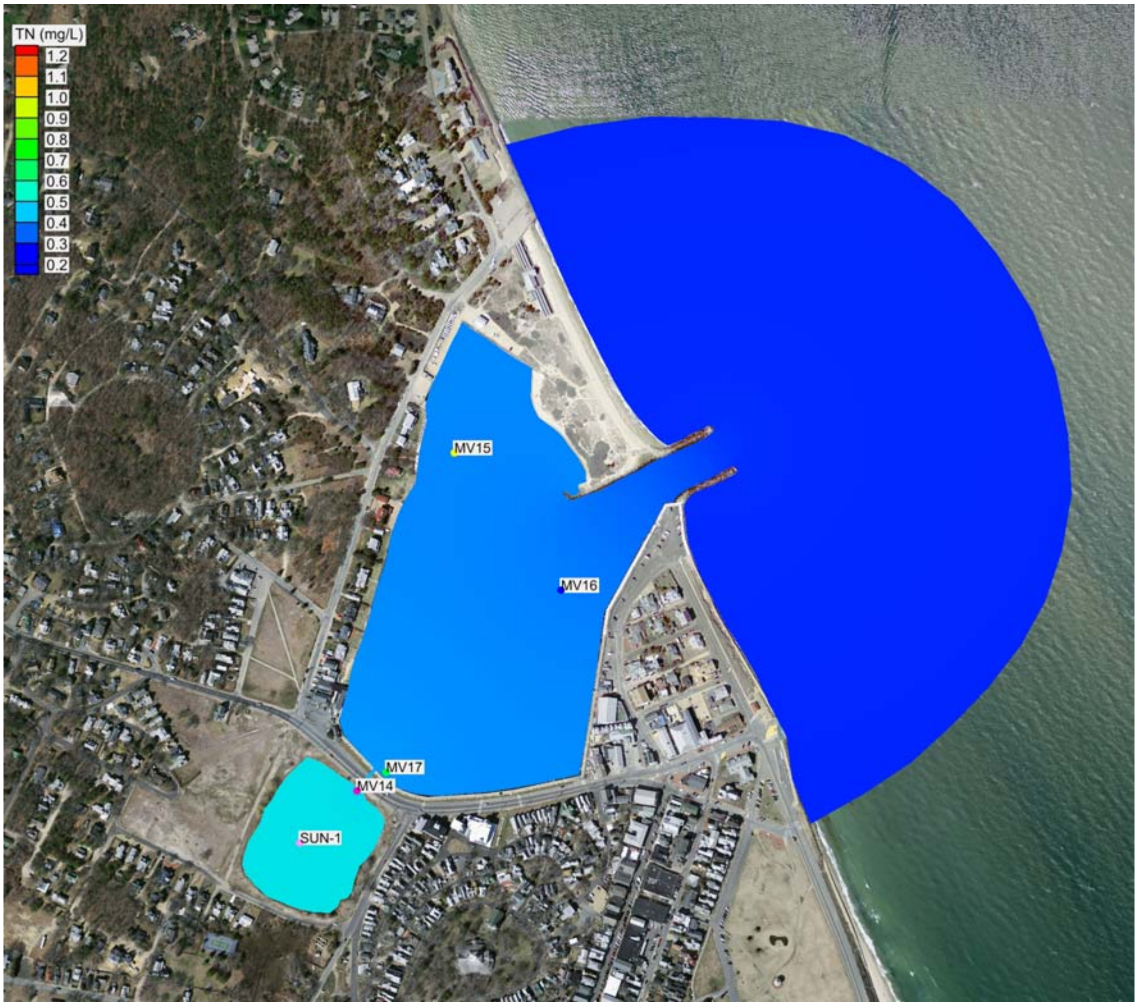


Figure VIII-1. Contour plot of modeled average total nitrogen concentrations (mg/L) in Oak Bluffs Harbor System, for threshold conditions (0.45 mg/L at water quality monitoring station SUN-1). The approximate location of the sentinel threshold station for Oak Bluffs Harbor System (SUN-1) is shown.

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

sub-embayment	present total load (kg/day)	threshold load (kg/day)	threshold % change
Oak Bluffs Harbor	5.540	6.386	+15.3%
Sunset Lake	7.704	10.123	+31.4%

Table VIII-4. Threshold sub-embayment loads and attenuated surface water loads used for total nitrogen modeling of the Oak Bluffs Harbor System, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	threshold load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Oak Bluffs Harbor	6.386	0.430	11.258
Sunset Lake	10.123	0.063	-5.631

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel stations is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station within Sunset Lake, a increase in TN concentration of approximately 9% was allowed at the Sentinel threshold station SUN-1.

Table VIII-5. Comparison of model average total N concentrations from present loading and the modeled threshold scenario, with percent change, for the Oak Bluffs Harbor System. Sentinel threshold station, SUN-1, to maintain benthic animal habitat within the System is in bold print. The nitrogen level to maintain benthic animal habitat in Sunset Lake is <0.45 mg TN.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Sunset Lake	MV-14	0.392	0.425	+8.4%
Oak Bluffs	MV-15	0.320	0.333	+4.0%
Oak Bluffs	MV-16	0.313	0.325	+3.8%
Oak Bluffs	MV-17	0.335	0.351	+4.8%
Sunset Lake	**SUN-1**	**0.408**	**0.446**	**+9.3%**

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.

IX. REFERENCES

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

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

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

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

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

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

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

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

Costa et al. 1999. Managing anthropogenic nitrogen inputs to coastal embayments: Technical basis and evaluation of a management strategy adopted for Buzzards Bay. Buzzards Bay Project Technical Report

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

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

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

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

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

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

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

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

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

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

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

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

Howes B.L., J.S. Ramsey, R.I. Samimy, D.R. Schlezinger, E.M. Eichner. 2010. Linked Watershed-Embayment Model to Determine the Critical Nitrogen Loading Threshold for the Farm Pond System, Oak Bluffs, Massachusetts. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

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

Horsley & Witten, Inc. with Wright Pierce Engineers. December 22 1997. Oak Bluffs Phase III Wastewater Facilities Plan and EIR. Town of Oak Bluffs Wastewater Facilities Planning Group.

IEP. 1988. Report on the Hydrology and Water Quality Characteristics of Farm Pond, Oak Bluffs, Martha's Vineyard, Massachusetts.

IEP. 1991. Final Environmental Impact Report, Farm Pond, Oak Bluffs, Martha's Vineyard, Massachusetts.

J. Forns 1983. Harthaven Inlet Study: Evaluation and Recommendations.

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

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

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

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

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

MV Commission (2003) Nutrient Loading to Lake Anthony and Sunset Lake

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

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

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

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

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

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

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

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

Oldale, R. N., Barlow, R.A. 1986. Geologic map of Cape Cod and the islands: U.S. Geological Survey Miscellaneous Investigations Series Map I-1763, 1 sheet, scale 1:100,000.

Oldale, R. N., 1992, Cape Cod and the Islands: The Geologic Story: Parnassus Imprints, Orleans, Massachusetts, 208 p.

Oldale, R. N. 2001. Cape Cod, Martha's Vineyard and Nantucket, The Geologic Story. On Cape Publications, Yarmouth Port, MA, 224p.

Oldale, R. N. 2001a The Geologic History of Cape Cod, Massachusetts USGS, Woods Hole Field Center, Massachusetts. URL: http://pubs.usgs.gov/gip/capecod/index.html

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

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

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

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

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

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

Schlee, J.S., and Pratt, R.M., 1970, Atlantic continental shelf and slope of the United States - gravels of the northeastern part: U.S. Geological Survey Professional Paper 529-J, 39 p.

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

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

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

Smith, K.N. 1999. Salt Marsh Uptake of Nitrate. M.A. Thesis Boston University Department of Earth Sciences. pp.76.

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

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

Taylor, J. 2003. Nutrient Loading to Lake Anthony and Sunset Lake. The Martha's Vineyard Commission. 0105-MWI, Vol. 2.

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

Uchupi, E. Giese, G.S., Aubrey, D.G.,Kim, D. J. 1996. The Late Quaternary construction of Cape Cod, Massachusetts - a reconsideration of the W. M. Davis model: Geological Society of America Special Paper 309, 69p.

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

Valiela, I. J.M. Teal, S. Volkmann, D. Shafer, and E.J. Carpenter. 1978. Nutrient and particulate fluxes in a salt marsh ecosystem: Tidal exchanges and inputs by precipitation and groundwater. Limnology and Oceanography 23:798-812.

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

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

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

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

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

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

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