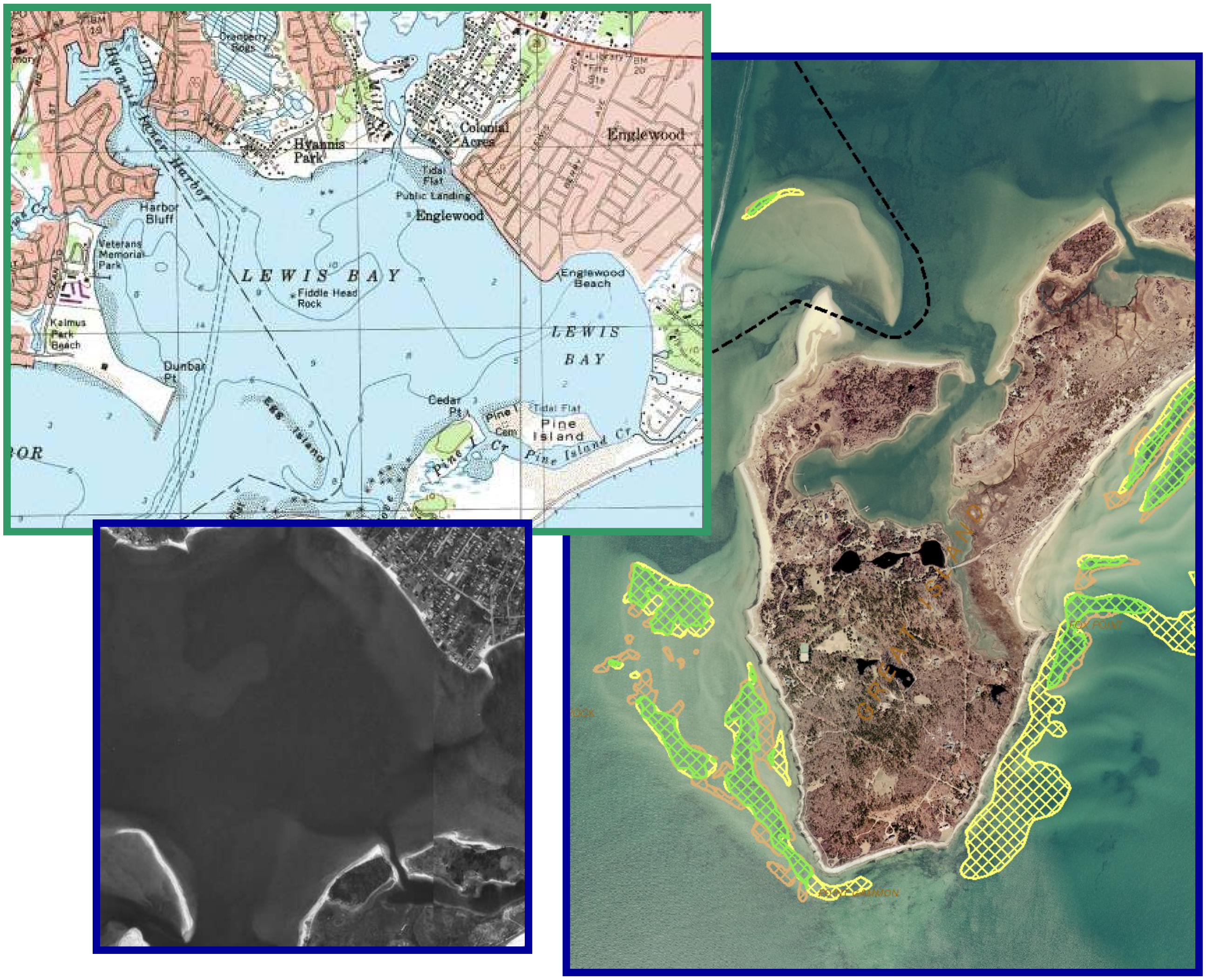
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Lewis Bay Embayment System, Barnstable/Yarmouth, MA



University of Massachusetts Dartmouth
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Massachusetts Department of
Environmental Protection

FINAL REPORT – December 2008

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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 Lewis Bay embayment system, a coastal embayment primarily within the Town of Barnstable, Massachusetts. Analyses of the Lewis Bay embayment system was performed to assist the Towns of Barnstable and Yarmouth with up-coming nitrogen management decisions associated with the current and future wastewater planning efforts of the Towns, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and harbor maintenance programs. As part of the MEP approach, habitat assessment was conducted on the embayment based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Towns of Barnstable and Yarmouth 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 Lewis Bay embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Towns) for the restoration of the Lewis Bay 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 Lewis Bay embayment system within the Towns of Barnstable and Yarmouth is at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater from the increasingly developed watershed to this coastal system. Eutrophication is a process that occurs naturally and gradually over a period of tens or hundreds of years. However, human-related (anthropogenic) sources of nitrogen may be introduced into ecosystems at an accelerated rate that cannot be easily absorbed, resulting in a phenomenon known as cultural eutrophication. In both marine and freshwater systems, cultural eutrophication results in degraded water quality, adverse impacts to ecosystems, and limits on the use of water resources.

The Towns of Barnstable and Yarmouth have recognized the severity of the problem of eutrophication and the need for watershed nutrient management and are currently developing Comprehensive Wastewater Management Plans, which each Town plans to implement. The Town of Barnstable has also completed and implemented wastewater planning in other regions of the Town not associated with the Lewis Bay embayment system. The Town has nutrient management activities related to their tidal embayments, which have been associated with the MEP effort in the Three Bays and the Centerville River/Harbor embayment systems. The Town of Barnstable and Yarmouth with associated work groups have recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making and alternatives analysis. The completion of this multi-step process has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, which is a partnership effort between all MEP collaborators and the Towns. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns' nutrient management groups to predict the impacts on water quality from a variety of proposed management scenarios.

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

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

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

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

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

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

For a comprehensive description of the Linked Model, please refer to the *Full Report: Nitrogen Modeling to Support Watershed Management: Comparison of Approaches and Sensitivity Analysis*, available for download at http://www.state.ma.us/dep/smerp/smerp.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.state.ma.us/dep/smerp/smerp.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.state.ma.us/dep/smerp/smerp.htm.

Application of MEP Approach: The Linked Model was applied to the Lewis Bay embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Town of Barnstable, with technical guidance from the Coastal Systems Program at SMAST (see Chapter II). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Barnstable and Yarmouth Planning Departments, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Lewis Bay embayment system and each of the systems sub-embayments as appropriate (current and build-out loads are summarized in Chapter IV). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Lewis Bay embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Vineyard Sound source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Lewis Bay 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 Lewis Bay embayment system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for the Lewis Bay 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 Lewis Bay embayment system in the Town of Barnstable and Yarmouth. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. 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 57% - 81% of the controllable watershed load to the Lewis Bay 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 Lewis Bay embayment system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure. At present, the Lewis Bay system is showing variations in nitrogen enrichment and habitat quality among its various component basins. In general the system is showing healthy to moderately impaired benthic habitat. However, the smaller tributary embayments and limited inner areas of Lewis Bay (e.g. Uncle Roberts Cove, Hyannis Inner Harbor) are presently moderately impaired based upon infaunal habitat criteria. However, the dominant habitat issue for this system is the significant impairment of the Lewis Bay basin and Uncle Roberts Cove, based on eelgrass criteria. Historical eelgrass beds have been lost in these areas and eelgrass is virtually non-existent within this system. These significantly impaired habitats comprise ca. 90% of the estuarine area of the Lewis Bay Embayment System.

Overall, the oxygen levels within the major sub-basins to the Lewis Bay Embayment System are indicative of relatively healthy or only moderately impaired conditions. This is based on the definition of the Hyannis Inner Harbor and Mill Pond basins as infaunal habitats (e.g. historically have not supported eelgrass) and consideration of each sub-basins physical structure and natural biogeochemical cycling. Similar to other embayments in southeastern Massachusetts, the inner basins evaluated in this assessment showed high frequency variation, apparently related to diurnal and tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration at each mooring site underscores the need for continuous monitoring within these systems.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate moderately nutrient enriched waters within each sub-embayment basin to Lewis Bay. The oxygen data is consistent with organic matter enrichment, primarily from phytoplankton production, as seen from the parallel measurements of chlorophyll a. The measured levels of oxygen depletion and enhanced chlorophyll a levels match the spatial pattern of total nitrogen concentrations in this system. The parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

At present, eelgrass exists only within a small portion at the tidal inlet of Lewis Bay. The absence of eelgrass throughout the Lewis Bay Embayment System is consistent with the observed moderate level of nutrient enrichment throughout each of the sub-embayments to this complex estuary. Total nitrogen levels (TN) within the lower basins that supported eelgrass in 1951 (Lewis Bay and Uncle Roberts Cove) have mean summertime levels of ~0.4 mg N L^{-1} compared to the levels at the outer beds in adjacent Hyannis Harbor of 0.30-0.35 mg N L^{-1} (monitoring data, Chapter VI). Other key water quality indicators, dissolved oxygen and chlorophyll a, show similar levels of moderate enrichment with periodic oxygen depletions below 5-4 mg/L and chlorophyll levels of 3-6 ug/l to 2-10 ug/l in the Lewis Bay basin and 5-15 ug/L in Uncle Roberts Cove. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, the loss of eelgrass in these basins is expected.

The infaunal study indicated an overall system supporting generally healthy to only moderately impaired infaunal habitat relative to the ecosystem types represented (i.e. embayment versus salt marsh creek/pond). The range of habitat quality within Lewis Bay, results from a gradient in nutrient related habitat degradation from the inland reaches to the high quality habitat near the tidal inlet. This gradient continues into Hyannis Harbor and Uncle Roberts Cove. While the basin of Mill Creek is naturally nutrient and organic matter enriched, the present conditions of macroalgae and high chlorophyll a levels suggest a moderate level of impairment for this system as well.

Overall, the infaunal habitat quality was consistent with the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to it being dominated by wetlands versus being more characteristic of a tidal embayment. Based upon the MEP analysis it is clear that the tributary sub-embayment basins are presently supporting moderately to significantly impaired benthic habitat, while the main basin of Lewis Bay is generally of high quality. The Mill Creek basin is supporting moderately impaired habitat for a salt marsh basin. Impairment in these basins is through nitrogen and organic matter enrichment. The results of the Infauna Survey indicate that nitrogen management in the Lewis Bay watershed needs to include a lowering of the level of nitrogen enrichment in Hyannis Inner Harbor and Uncle Roberts Cove and potentially in Mill Creek thereby leading to restoration of nitrogen impaired benthic habitats. However, it is important to note that in general the Lewis Bay Embayment System is supportive of high quality infauna habitat throughout much basin area.

3. Conclusions of the Analysis

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

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

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Town of Barnstable Lewis Bay embayment system was comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 57% - 81% of the controllable watershed nitrogen load to the embayment was from wastewater.

A major finding of the MEP clearly indicates that a single 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, the analysis of the adjacent Rushy Marsh system and the Pleasant Bay and Nantucket Sound embayments associated with the Town of Chatham. This is almost certainly going to be true for the other embayments within the MEP area, as well, inclusive of Lewis Bay.

The threshold nitrogen levels for the Lewis Bay embayment system in Barnstable and Yarmouth were determined as follows:

Lewis Bay Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Lewis Bay system should reflect both recent pre-degradation habitat quality and be reasonably achievable. Based upon the assessment data (Chapter VII), the Lewis Bay system is presently supportive of habitat in varying states of impairment, depending on the component sub-basins of the overall system.

- The primary habitat issue within the Lewis Bay Embayment System relates to the loss of the extensive eelgrass beds from Lewis Bay and the shallow marginal beds from Uncle Roberts Cove. This loss of eelgrass classifies these areas as "significantly impaired", although Lewis Bay presently supports generally high quality infaunal communities. The impairments to both the infaunal habitat and the eelgrass habitat within the component basins of the Lewis Bay Embayment System are supported by the variety of other indicators, oxygen depletion, chlorophyll, and TN levels, which support the conclusion that these impairments are the result of nitrogen enrichment, primarily from watershed nitrogen loading.

- The results of the water quality and infaunal data, coupled with the temporal trends in eelgrass coverage, clearly support the need to lower nitrogen levels within Lewis Bay and Uncle Roberts Cove in order to restore eelgrass habitat. Lesser loading reductions would be necessary within Hyannis Inner Harbor and potentially in Mill Creek for restoration of nitrogen impaired benthic habitats. Restoration of the limited areas of moderately impaired and areas of significantly impaired infaunal habitats within Lewis Bay and Uncle Roberts Cove, respectively, will be achieved with the restoration of eelgrass habitat within these basins.

- The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location (BHY-3) within Lewis Bay was determined to be 0.38 mg TN L^{-1}. As there is not high quality eelgrass habitat within the Lewis Bay Embayment System, this threshold was based upon comparison to other local embayments of similar depths and structure under MEP analysis as well as conditions near the eelgrass areas adjacent the tidal inlet to Hyannis Harbor. A well studied eelgrass bed within the lower Oyster River (Chatham) has been stable at a tidally averaged watercolumn TN of 0.37 mg N L^{-1}, while eelgrass was lost within the Lower Centerville River at a tidally averaged TN of 0.395 mg N L^{-1}, and also within Waquoit Bay at 0.39 mg N L^{-1}.

- The selection of the TN level for the shallow marginal bed within Uncle Roberts Cove followed the process noted in Chapter VIII for the selection of a sentinel station. Since water depth is important in determining the criteria for eelgrass restoration, as the same phytoplankton concentration that results in shading of eelgrass in deep water will allow sufficient light to support eelgrass in shallow water, the shallower water at the upper basin site allows for a higher TN level compared to the sentinel station. Analysis of comparable beds within the Green Pond Estuary (Falmouth) recommends the secondary criteria for this site as 0.40 mg TN L^{-1} for stability. The target nitrogen concentration for restoration of eelgrass within the lower basin of Green Pond, was determined to be 0.40 mg TN L^{-1} based in part upon the findings that: (1) eelgrass beds have been lost in that basin at 0.41 mg TN L^{-1}, although sparse eelgrass were observed adjacent the inlet, (2) eelgrass beds in Bournes Pond in very shallow water persisted at 0.42 mg TN L^{-1}. It should be noted that 0.40 mg N L-1 within Uncle Roberts Cove is a secondary criteria to ensure restoration of eelgrass habitat within this sub-embayment and should be met when the threshold is met at the sentinel station in Lewis Bay.

- Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fisheries resources), benthic infaunal habitat quality must also be supported as a secondary condition. At present, the regions with moderately impaired infaunal habitat within the Hyannis Inner Harbor and the potentially impaired habitat within Mill Creek have total nitrogen (TN) levels in the range of 0.518 - 0.574 mg N L^{-1}. Based upon observations discussed in Chapter VIII, the MEP Technical Team concluded that an upper limit of 0.50 mg N L^{-1} tidally averaged TN would support healthy infaunal habitat in the Lewis Bay System, specifically areas with moderately impaired infaunal habitat.

- For restoration of the Lewis Bay Embayment System, both the primary nitrogen threshold at the sentinel station and the secondary criteria within the sub-embayments need to be achieved. However, the secondary criteria established by the MEP are to merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station. Three secondary criteria were established for the Lewis Bay Embayment System: (1) a TN level of 0.40 mg N L^{-1} was set to restore the shallow marginal eelgrass bed within Uncle Roberts Cove (tidal average at BHY-4), this will also ensure restoration of infaunal habitat throughout that basin; (2) a tidally averaged TN level of <0.5 mg N L^{-1} with the Hyannis Inner Harbor basin (average of BH-1 and BH-2) and (3) a tidally averaged TN level of <0.5 mg N L^{-1} within the salt marsh basin of Mill Creek to reduce the magnitude of the phytoplankton blooms and improve infaunal habitat in the lower basin.

- Based upon all lines of evidence it appears that the Halls Creek Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment. Putting all the MEP habitat assessment elements together, it appears that for Halls Creek, the critical values are a total nitrogen level of 2 mg N L^{-1} in the headwaters (Station BC-13) and a level of 1 mg N L^{-1} at the border of the upper and lower reach (Station BC-14). As this upper/lower boundary station is the uppermost long-term marine water quality sampling site and integrates all of the watershed and upper marsh nitrogen inputs and removals, it was selected as the sentinel station for this system (BC-14). The threshold (tidally averaged) total nitrogen level of 1 mg N L^{-1} was determined to be appropriate for the sentinel station (BC-14).

For restoration of the Lewis Bay Embayment System, both the primary nitrogen threshold at the sentinel station and the secondary criteria within the sub-embayments need to be achieved. However, the secondary criteria established by the MEP are to merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station. It should be emphasized that these secondary criteria values were not used for setting nitrogen thresholds in this embayment system. The results of the Linked Watershed-Embayment modeling are used to ascertain that when the nitrogen threshold is attained, TN levels in the regions associated with the secondary criteria are within the acceptable range. The goal is to achieve the nitrogen target at the sentinel location and restore eelgrass habitat throughout Lewis Bay and Uncle Roberts Cove as well as infaunal habitat throughout the System

It is important to note that the analysis of future nitrogen loading to the Lewis Bay estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that significant increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. Therefore, watershed-estuarine nitrogen management must include management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Lewis Bay estuarine system is that restoration will necessitate a reduction in the present (2004) nitrogen inputs and management options to negate additional future nitrogen inputs.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Lewis Bay system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Surface water loads to estuarine waters of the Lewis Bay system are presented separately from the loads of the sub-embayments to which they discharge.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
LEWIS BAY SYSTEM										
groundwater sources										
Lewis Bay	0.564	4.364	26.490	1.825	30.855	13.507	25.999	70.361	0.37-0.43	0.38
Uncle Roberts Cove	0.096	0.148	0.214	0.033	0.540	0.759	12.771	14.069	0.41	0.40
Mill Creek	0.405	1.748	13.570	0.545	15.964	0.627	-1.535	15.056	0.52-0.56	0.50
Hyannis Inner Harbor	0.485	4.121	6.847	1.718	12.153	0.633	18.660	31.445	0.43-0.60	0.50
Snows Creek	0.293	2.074	7.970	11.559	15.115	-	-4.533	10.582	1.57	--
Stewarts Creek	0.485	4.312	21.564	19.485	38.992	0.236	-9.750	29.478	1.25	--
surface water sources										
Chase Brook [a]	0.140	1.077	2.488	0.000	3.345	-	-	3.345	-	--
Mill Pond Creek [a]	1.033	6.101	10.425	0.471	15.038	-	-	15.038	-	--
Inner Harbor Creek [b]	0.060	0.326	1.907	0.178	1.907	-	-	1.907	-	--
Lewis Bay System Total	3.562	24.271	91.475	35.814	133.909	15.762	41.612	191.283	**0.37-1.57**	**0.38**

[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 unattenuated 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. Atmospheric loads to surface water inputs are included with their respective watershed load.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 2001 – 2006 data, ranges show the upper to lower regions (highest-lowest) of a sub-embayment.
[8] Eel grass threshold for sentinel site located in Lewis Bay (0.38 mg/L), and infaunal targets at remaining stations.
[a] Surface water discharge to Mill Creek
[b] Surface water discharge to Hyannis Inner Harbor

Table ES-2. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Halls Creek system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Halls Creek system include both upper watershed regions contributing to the major surface water inputs.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
HALLS CREEK SYSTEM										
Halls Creek	0.844	10.151	11.383	-	21.534	0.630	5.252	27.416	0.43-0.45	1.00
Halls Creek (freshwater)	0.060	0.108	0.301	2.708	1.597	-	-	1.597	1.21	
Halls Creek System Total	0.904	10.259	11.384	2.708	23.131	0.630	5.252	29.013	**0.43-1.21**	**1.00**

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 unattenuated 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 data collected between 2001 and 2006, ranges show the upper to lower regions (highest-lowest) of the indicated sub-embayment.
8 threshold for sentinel site located at mid-point WQ monitoring station of the system.

Table ES-3. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Lewis Bay system.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
LEWIS BAY SYSTEM						
groundwater sources						
Lewis Bay	30.855	9.663	13.507	23.916	47.086	-68.7%
Uncle Roberts Cove	0.540	0.54	0.759	10.991	12.290	0.0%
Mill Creek	15.964	4.321	0.627	-1.208	3.740	-72.9%
Hyannis Inner Harbor	12.153	7.115	0.633	9.780	17.528	-41.5%
Snows Creek	15.115	16.233	-	-4.533	11.700	+7.4%
Stewarts Creek	38.992	41.605	0.236	-10.402	31.439	+6.7%
surface water sources						
Chase Brook	3.345	3.337	-	-	3.337	-0.2%
Mill Pond Creek	15.038	14.682	-	-	14.682	-2.4%
Inner Harbor Creek	1.907	0.326	-	-	0.326	-82.9%
Lewis Bay System Total	133.909	97.822	15.762	23.916	137.500	-26.9%

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

Table ES-4. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Halls Creek system.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent change in watershed load to achieve allowed threshold load levels
HALLS CREEK SYSTEM						
Halls Creek	21.534	32.918	0.630	6.649	40.197	+52.9%
Halls Creek (freshwater)	1.597	3.345	-	-	3.345	+109.4%
Halls Creek System Total	23.131	36.263	0.630	6.649	43.542	+56.8%

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

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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 Town of Barnstable Water Quality Monitoring Program, the Town of Yarmouth Water Quality Monitoring Program, the Three Bays Water Quality Monitoring Program, the Lewis Bay Research Center and SMAST "volunteers". The Monitoring of the Lewis Bay System was truely a coordinated joint effort between these Towns, their citizens and staff. These individuals gave of their time to collect nutrient related water quality from this system, without which the present analysis would not have been possible. Of particular note are Lindsey Counsell of Three Bays Preservation, Coordinator of the Three Bays Monitoring Program, and John Jacobsen and Dale Saad of the Town of Barnstable, Coordinators of the Barnstable Town-wide Monitoring Program; Karl von Honne and Conrad Caia, Coordinators of the Yarmouth Town-wide Monitoring Program. Similarly, many in the Town of Barnstable helped in this effort, the Barnstable Department of Public Works and the Barnstable Shellfish Department, as well as the Barnstable Nutrient Management Committee; many in the Town of Yarmouth, but particularly the Nutrient Management Group and the Department of Public Works. The technical team would like to specifically acknowledge the efforts of Mark Els and George Allaire for helping to move this effort forward from its inception and to Three Bays Preservation for their energy and perseverance in the stewardship of one of the regions key coastal resources.

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I. INTRODUCTION

The Lewis Bay Embayment System is a complex estuary located within the Towns of Barnstable and Yarmouth on Cape Cod, Massachusetts with a southern shore bounded by water from Nantucket Sound (Figure I -1 and I-2). The estuary is composed of a lagoon formed behind a barrier spit (Dunbar Point) and bounded to the south by Smiths Point on Great Island. Lewis Bay is comprised of a number of sub-embayments tributary to the main basin such as Hyannis Inner Harbor, Mill Creek, and Uncle Roberts Cove. Just seaward of Dunbar Point which defines the entrance to the main basin of Lewis Bay is an area of previously open water that is currently sheltered by a constructed breakwater thereby defining what is commonly referred to as Hyannis Harbor into which discharges Stewarts Creek.

The Lewis Bay watershed is also distributed only between the Town of Barnstable and the Town of Yarmouth. A large portion of the overall watershed includes the sub-watersheds contributing direct groundwater discharge to the estuary and contributing to the five surface water discharges flowing to the Hyannis Harbor portion of the system (Stewarts Creek), directly into Lewis Bay (Snows Creek, Creek from Hospital Bog) or into the salt marsh basin of Mill Creek (stream from Mill Pond and Chase Brook). Although land-uses closest to an embayment generally have greater impact than those in the upper portions of the watershed, which are subject to nitrogen attenuation during transport through natural aquatic systems (e.g. ponds, rivers, wetlands etc.) prior to discharge to the embayment, effective restoration of the Lewis Bay System, will require the Towns to be active in nutrient management throughout the watershed to the overall system.

The number of sub-embayments (Hyannis Inner Harbor, Mill Creek, and Uncle Roberts Cove) to the Lewis Bay System greatly increases the shoreline and decreases the travel time of groundwater (and its pollutants) from the watershed recharge areas to bay regions of discharge. 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 particular, the Lewis Bay system and its sub-embayments along the Barnstable and Yarmouth shores are at risk of eutrophication (over enrichment) from high nitrogen loads in the groundwater and runoff from the associated watersheds.

The Lewis Bay embayment system is a complex estuary with one inlet connecting the main basin to Nantucket Sound through the artificial basin of Hyannis Harbor. The Lewis Bay Embayment System consists primarily of the large main lagoonal basin of Lewis Bay with three tributary sub-embayments (Figure I-1 and Figure I-2). Lewis Bay terminates on its northern shore in two distinctly different aquatic environments, one being a salt marsh system commonly referred to as Mill Creek, the other being Hyannis Inner Harbor which services marinas, boatyards, restaurants and an active ferry terminal. The third sub-embayment is located on the barrier spit, Uncle Roberts Cove. Lewis Bay abuts Nantucket Sound and is bounded to the west by Kalmus Park Beach in the vicinity of the inlet to the estuary and Smiths Point located along the most eastern boundary of the entrance to Lewis Bay on Grand Island. The Lewis Bay Estuary receives twice daily tidal waters from Nantucket Sound. The inlet to Lewis Bay is a feature that prior to being armored, very likely migrated along the beach as a function of longshore transport of sediments and coastal storms effectively impinging on the waters of the

Figure I-1. Study area for the Massachusetts Estuaries Project analysis of the Lewis Bay Embayment System. Tidal waters enter to the main basin of Lewis Bay through a single large inlet from Nantucket Sound. Freshwaters enter from the watershed primarily through direct groundwater discharge and 4 surface water discharges (Snows Creek, a creek from Hospital Bog, a stream from Mill Pond and Chase Brook) and discharge through the Stewarts Creek Salt Marsh adjacent the outer basin, Hyannis Harbor.

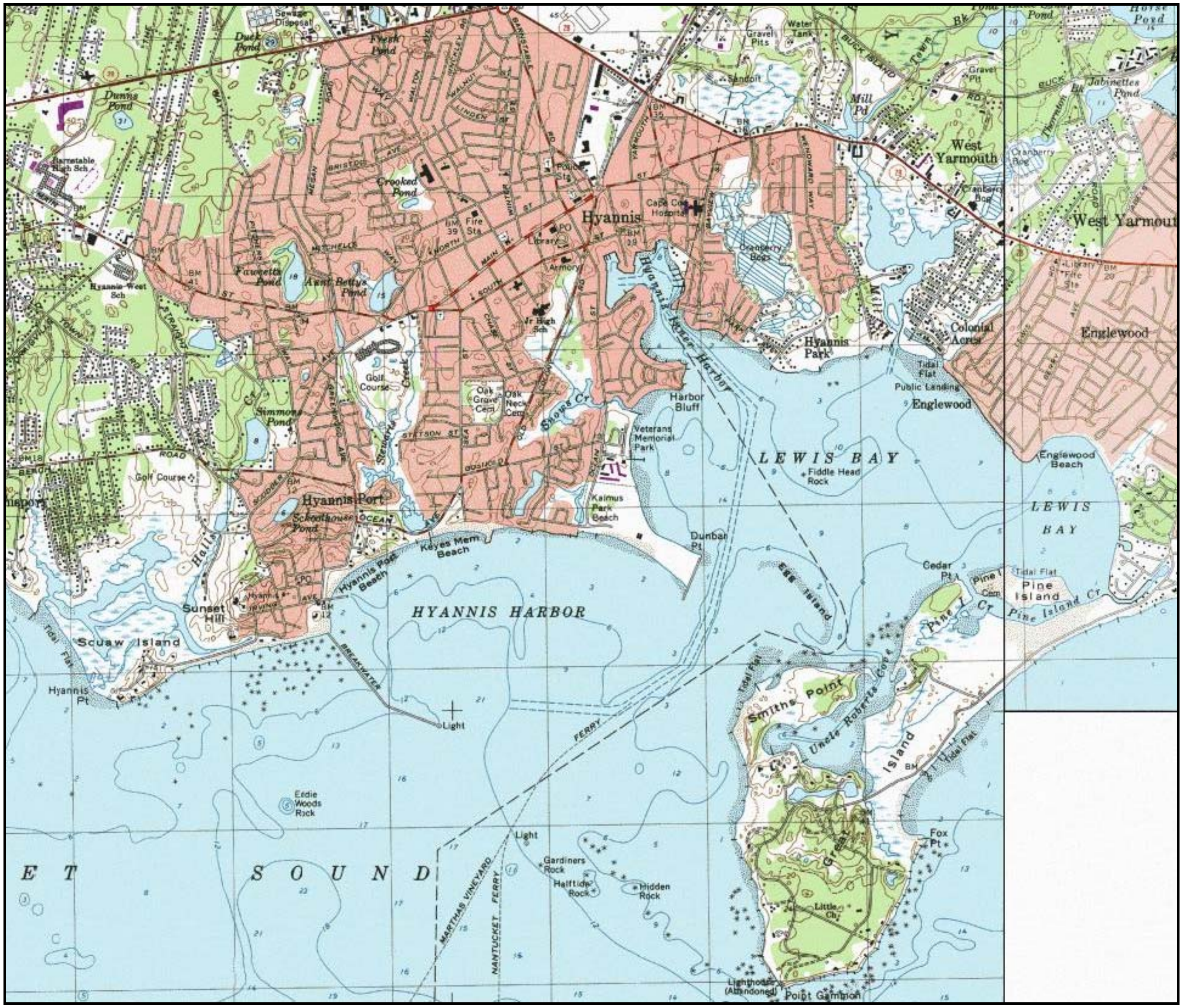


Figure I-2. Topographic Map of the Lewis Bay System depicting major geographic features. Note the barrier spit that joined Great Island to the mainland and created Lewis Bay.

inlet. Even as an armored feature, the inlet to Lewis Bay is characterized by shifting sand shoals (Egg Island), which must be periodically dredged to maintain navigability of the channel in and out of the system. Currently, the armored inlet is stable and the Town of Barnstable periodically dredges the inlet channel to keep the inlet and Hyannis Harbor-Lewis Bay navigable.

The present Lewis Bay system results from tidal flooding of small drowned river valleys formed primarily by the streams discharging into Stewarts Creek, Snows Creek and Mill Creek and the formation of the Lewis Bay lagoon by coastal processes. Drowning of the river valleys occurred gradually as a result of rising sea level following the last glaciation approximately 18,000 years BP. The extension of the barrier spit, is much more recent.

The primary ecological threat to the Lewis Bay System as a coastal resource is degradation resulting from nutrient enrichment. Although the significantly enclosed portions of the Lewis Bay estuarine system (Stewarts Creek, Snows Creek, Hyannis Inner Harbor, Mill Creek, Uncle Roberts Cove) have varying and periodic levels of bacterial contamination related to stormwater run-off from the watershed, these do not appear to be having large system-wide impacts. Bacterial contamination causes periodic closures of shellfish harvest areas within the Mill Creek (SC28.5) sub-embayment as well as portions of Hyannis Inner Harbor (SC28.2), Snows Creek (SC28.8) and the northeastern shore of Lewis Bay (SC28.7). In contrast, loading of the critical eutrophying nutrient, nitrogen, to the Lewis Bay System has greatly increased over recent decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to the Lewis Bay Estuary, like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater.

The Towns of Barnstable and Yarmouth have been among the fastest growing towns in the Commonwealth over the past two decades. Hyannis is predominantly on municipal sewers in the dense downtown areas which flow to the Barnstable Wastewater Treatment Facility, with treated effluent discharged within the Lewis Bay, Hyannis Harbor (Stewarts Creek) and Halls Creek sub-watersheds. Even so, the vast majority of the Lewis Bay System watershed is not connected to any municipal sewerage system and wastewater treatment and disposal is primarily based on privately maintained septic systems. As existing and future increased levels of nutrients impact the coastal systems of Barnstable and Yarmouth, water quality degradation will accelerate, with further harm to invaluable environmental resources.

As the primary stakeholder to the Lewis Bay System, the Towns of Barnstable and Yarmouth were among the first communities to become concerned over perceived degradation of the Bay's environments. The concern over declining habitat quality led directly to the establishment by both municipalities of comprehensive water quality monitoring programs aimed at determining the degree to which the waters of each Town might be impaired by nitrogen enrichment. The Towns of Barnstable and Yarmouth Water Quality Monitoring Programs coordinated efforts on the shared resource waters of Lewis Bay, with technical and analytical assistance provided by the Coastal Systems Program at SMAST-UMD. This successful joint effort provided the high quality quantitative water column nitrogen data (2001-2006) required for the implementation of the MEP's Linked Watershed-Embayment Approach used in the present study.

The common focus of the coordinated Barnstable-Yarmouth Water Quality Monitoring effort has been to gather site-specific data on the current nitrogen related water quality throughout the Lewis Bay System and determine its relationship to watershed nitrogen loads. This multi-year effort has provided the necessary baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. The MEP effort builds upon the Water Quality Monitoring Program, and considers as appropriate previous historical hydrodynamic analyses (conducted by ASA, Inc. for Tetra Tech EM, Inc.) and water quality analyses. The MEP approach includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for each major sub-embayment. These critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater planning and nitrogen management alternatives development needed by the Town of Barnstable and Yarmouth. 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, inclusive of members of the local non-governmental organization (NGO) Three Bays Preservation.

The modeling tools developed as part of this program provide the quantitative information necessary for the Towns of Barnstable and Yarmouth 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 Lewis Bay System has been significantly altered by human activities over the past ~100 years or more (see Section I.2, below). As a result, the present nitrogen "overloading" appears to result partly from alterations to the geomorphology and some of its buffering ecological systems. These alterations subsequently affect nitrogen loading and transport within the watershed and influence the degree to which nitrogen loads impact the estuary. Therefore, restoration of this system should focus on managing nitrogen through both management of nitrogen loading within the watershed and restoration/management of processes which serve to lessen the amount or impact of nitrogen entering the estuary.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

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

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 Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts.

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 DEP and municipalities with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an outline of an implementation plan. For this project, the DEP 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, DEP 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.

In appropriate estuaries, bacterial technical reports will be developed in support of a Cape Cod wide TMDL for bacterial contamination. As possible, these analyses of bacterial contamination will be conducted in concert with the nutrient effort (particularly if there is a 303d listing), as was the case for the Prince’s Cove sub-embayment to the Three Bays system. Currently, the MEP (through SMAST) has not been tasked with a technical assessment of bacterial contamination in the Lewis Bay System for inclusion of this system into the Cape Cod wide bacterial TMDL that the MassDEP is in the process of producing.

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

The major MEP nitrogen management goals are to:

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

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

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

The Linked Model has been applied for watershed nitrogen management in approximately 30 embayments throughout southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach's greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options.

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

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

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

I.2 SITE DESCRIPTION

The Lewis Bay Embayment System exchanges tidal water with Nantucket Sound through one inlet at the southern end of the system demarcated by a barrier spit (Dunbar Point) and bounded to the south by Smiths Point on Great Island. The inlet connecting Lewis Bay to Hyannis Harbor on the seaward side of Dunbar Point is maintained by periodic dredging and is armored on the west side and remains in a "natural" un-stabilized state on the east side (Smiths Point). Nantucket Sound exhibits a moderate to low tide range, with a mean range of about 2.5 ft. Since the water elevation difference between Nantucket Sound and the Lewis Bay System is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle (note the tide range off Stage Harbor Chatham is ~4.5 ft, Wellfleet Harbor is ~10 ft).

Tidal damping (reduction in tidal amplitude) through an embayment can range from negligible, indicating "well-flushed" conditions, or show tidal attenuation caused by constricted channels and marsh plains, indicating a "restrictive" system, where tidal flow and the associated flushing are inhibited. Tidal data indicate only minimal tidal damping through the inlet into the Lewis Bay system. It appears that the tidal inlet is operating efficiently being that it is periodically dredged to maintain navigability. Within the Hyannis Inner Harbor, Mill Creek and Uncle Roberts Cove portion of the System, the tide propagates to the sub-embayments with negligible attenuation, consistent with generally well-flushed conditions throughout.

For the MEP analysis, the Lewis Bay Estuarine System has been partitioned into four general sub-embayment groups: the 1) Lewis Bay, 2) Hyannis Inner Harbor, 3) Mill Creek, and 4) Uncle Roberts Cove as depicted in Figure I-1. Hyannis Harbor with Stewarts Creek was examined as an outer basin as it effects the boundary waters of Nantucket Sound which flow through it to Lewis Bay.

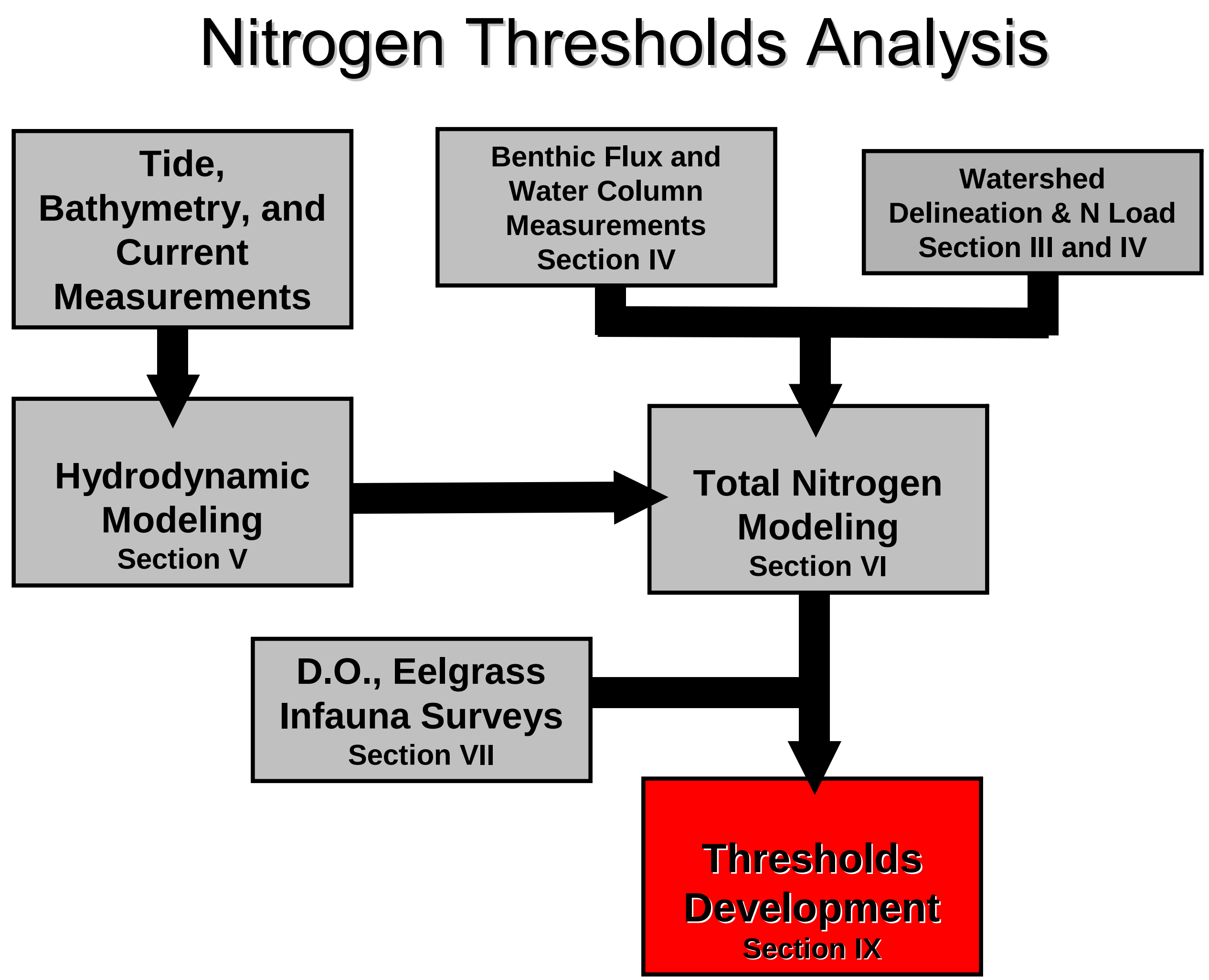


Figure I-3. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

The overall Lewis Bay System supports a diversity of estuarine habitats, including the main open water embayment basin of Lewis Bay, the salt marshes of Snow Creek and Mill Creek and the dredged harbor basin of Hyannis Inner Harbor. The Mill Creek basin functions primarily as a salt marsh "pond" of shallow depth with large bordering tidal marshes. Mill Creek is a moderately nutrient enriched sub-basin. However, as to the extent that it is functioning as primarily a salt marsh basin, it's level of impairment has been unclear. The present MEP analysis takes into account the much lower sensitivity of salt marshes to nutrient inputs compared to tidal embayments, so as to establish the proper nutrient threshold for restoration/protection of this estuarine system.

Most of the Lewis Bay System's salt marsh area is to the north and associated with Mill Creek with shallow tidal flats and large fluctuating salinity. In contrast, the main basin of Lewis Bay shows more typical embayment characteristics with a mixture of open water areas and channels, small fringing salt marshes and relatively stable salinity gradients.

I.3 NUTRIENT LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In sandy glacial outwash aquifers, such as in the watershed to the Lewis Bay System, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer minerals (Weiskel and Howes 1992). Since even 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). 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). Tidal reaches within the Lewis Bay Estuary follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

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

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

Protection and restoration of coastal embayments from nitrogen overloading has resulted in a focus on determining the assimilative capacity of these aquatic systems for nitrogen. While this effort is ongoing (e.g. USEPA TMDL studies), southeastern Massachusetts 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). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the "allowable N concentration increase" or "threshold nitrogen concentration" used in previous studies had a significant uncertainty due to the need for direct linkage of watershed and embayment models and site-specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout the Lewis Bay System monitored by the Town of Barnstable and Yarmouth. Data from the Water Quality Monitoring Program combined with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) was utilized to "tune" general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, almost all of the estuarine reaches within the Lewis Bay System are presently beyond their ability to assimilate additional nutrients without impacting their ecological health (nitrogen related habitat impairment). Nitrogen levels are elevated throughout the System and eelgrass beds have been lost from this system for more than a decade. Nitrogen related habitat impairment within the Lewis Bay Estuary shows a gradient of high to low moving from the inland, less well flushed sub-basins, to the tidal inlet. The result is that nitrogen management of the Lewis Bay System is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed "eutrophication" and in certain instances can occur naturally over long periods of time. When the nutrient loading is rapid and primarily from human activities leading to changes in a coastal watershed, nutrient enrichment of coastal waters is termed "cultural eutrophication". Although it is clear that human-induced changes have increased nitrogen loading to this estuary and contributed to the degradation of its resources, the MEP analysis also examined the level to which eutrophication within the Lewis Bay sub-embayments (e.g. Uncle Roberts Cove, Mill Creek, Snows Creek, Stewarts Creek, Halls Creek) could potentially result from natural processes. Both natural and human-induced changes to an estuary must be considered in the nutrient threshold analysis. While this finding would not change the need for restoration, it would change the approach and potential targets for management. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment or sub-embayment into a "pristine" system.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important "boundary conditions" (e.g. watershed derived and offshore nutrient inputs) for water quality modeling of the Lewis Bay System; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within each component of the 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 Lewis Bay System, including the tributary sub-embayments of Snows Creek, Hyannis Inner Harbor, Mill Creek, and Uncle Roberts Cove. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for each of the systems. Once the hydrodynamic properties of each 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 watershed delineations by USGS using a modification of the West Cape model for sub-watershed areas designated by MEP. Almost all watershed sourced nitrogen entering the Lewis Bay System is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Nantucket Sound source waters and throughout the Lewis Bay system were provided by the coordinated Town of Barnstable and Yarmouth Water Quality Monitoring Program. Measurements of the salinity and nitrogen distributions throughout estuarine waters of the Lewis Bay System (2001-2006) were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Lewis Bay System for the Towns of Barnstable and Yarmouth. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission data and offshore water column nitrogen values were derived from an analysis of monitoring stations in Nantucket Sound (Section IV). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Section IV. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of the component sub-embayments was performed that included a review of existing water quality information and the results of a benthic analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration/protection of the Bay in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined system threshold for restoration or protection. This latter assessment represents only one of many solutions and is produced to assist the Towns in developing a variety of alternative nitrogen management options for this system. Finally, analyses of the Lewis Bay System were undertaken relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of dredging options to improve nitrogen related water quality. The results of the nitrogen modeling for each scenario have been presented in Section IX.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

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

These tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. The present Massachusetts Estuaries Project (MEP) study focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Lewis Bay 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 or unique features.

A number of studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Lewis Bay System over the past decade. A preliminary analysis of the circulation and nitrogen loading was performed, ca. 2001 for the Bureau of Resource Protection, Massachusetts Department of Environmental Protection (Tetra Tech EM Inc. 2005). The study was an initial assessment of watershed nitrogen loading to Lewis Bay (inclusive of Parker’s River and Swan Pond). The project employed an earlier generation watershed loading model (Waquoit Bay Nitrogen Loading Model, Valiela et. al., 1996), which pre-dates the MEP Linked Watershed-Embayment Modeling Approach. Loading was based upon a historical watershed derived by the Cape Cod Commission based upon available water table elevations. The watershed loading estimates were based upon MASSGIS land-use data, rather than local municipal assessors data. No site specific nitrogen attenuation measurements were made relative to the surface freshwater systems within the Bay's watershed and approximations were used to determine the load from the Hyannis WWTF. The hydrodynamic modeling employed RMA Numerical Models, but collection of data against which the model performance could be assessed, was limited by the project's scope. For example, two tide gages were deployed for 29 days in the summer of 2001, one in upper Lewis Bay and the other in Mill Creek in order to calibrate the hydrodynamic model simulations, however the offshore driving tide was not measured.

Review of the results relative to the Lewis Bay system, brought forward a variety of issues, summarized below:

- This model is not calibrated nor validated relative to Total Nitrogen within the waters of the Lewis Bay System (i.e. modeled results were not compared to observation data).

- The watershed N model employed general nitrogen loading and attenuation factors and is not site specific (an occupancy rate of 1.79 people per house for each system compared to the 2000 Census data which lists Barnstable as having a rate of 2.44). No assessment of seasonal occupancy was made.

- As regards the WWTF nitrogen plume analysis:

  1. Total Nitrogen levels in discharged effluent estimates were based upon only inorganic forms (ammonium and nitrate), without inclusion of the organic fraction;

  2. Ratios of TN/Cl from 4 groundwater sampling wells at various distances from the discharge site were used to determine denitrification during transport using a linear regression approach, but the statistical analysis showed a very weak relationship, with the near regressions functionally based on a single point. The result suggested a 57% loss of nitrogen during aquifer transport, in spite of detailed wastewater plume studies by the USGS (Ashumet Valley Plume, Tri-Town Septage Facility in Orleans) and MEP (West Falmouth WWTF) showing negligible removal in Cape Cod soils;

  3. Much of the error in the WWTF TN load can be attributed to the assumption by the project team that the effluent discharge was ca. 28 mg N/L, rather than the 5 mg N/L measured by the facility as part of its discharge permit.

Given that this was a preliminary effort and did not use site-specific land-use or nitrogen attenuation factors, had limited data collection to support the hydrodynamic modeling and did not calibrate/validate the water quality model, and since the watershed delineation has been refined by the MEP and USGS using the West Cape groundwater model, the MassDEP has determined that the present MEP assessment and modeling effort should supersede its previous project and provides the sufficient accuracy for watershed nitrogen management planning, under the CWMP process.

An important ecological restoration effort within the Lewis Bay System has recently been initiated by the US Army Corps of Engineers in collaboration with the Town of Barnstable. The project is focused upon the restoration of the Stewarts Creek Salt Marsh, which is tidally restricted at its outlet to Hyannis Harbor (Stewarts Creek Restoration Project) Stewarts Creek is a 55 acre tidal wetland site whose inlet has been restricted by a roadway/culvert. The salt marsh pond drains into Hyannis Harbor through a 60-foot-long, 3-foot diameter culvert, and the restriction has resulted in degradation of the salt marsh system. The major feature of the project includes the construction of a new, larger inlet to the pond to replace the existing culvert. Improving tidal flow is expected to restore the degraded salt marsh and riverine/ benthic habitat, including open water habitat. The restoration is scheduled to start in October of 2007 and be completed in 2008.

The Towns of Barnstable and Yarmouth, while both being actively engaged in the study and management of municipal infrastructure and natural resources, committed early on to gathering baseline water quality monitoring data in support of the MEP. Each Town operates a Water Quality Monitoring Program collecting water quality data on all of its embayment systems. The focus of the effort has been to gather site-specific data on the current nitrogen related water quality to support evaluations of observed water quality and habitat health. Water quality monitoring of the Lewis Bay System has been a joint coordinated effort initiated in 2001 with support from Three Bays Preservation and the Coastal Systems Programs at SMAST-UMD. The Barnstable/Yarmouth Water Quality Monitoring Program for Lewis Bay developed the baseline data from sampling stations distributed throughout the main basin and its tributaries (Figure II-1). Additionally, as remediation plans for this and other various systems are implemented throughout the Towns of Barnstable and Yarmouth, the continued monitoring is planned to provide quantitative information to the Towns relative to the efficacy of remediation efforts.

The joint Town of Barnstable/Yarmouth Water Quality Monitoring Program provided the quantitative water column nitrogen data (2001-2006) required for the implementation of the MEP's Linked Watershed-Embayment Approach. The MEP effort also builds upon previous watershed delineation and land-use analyses, the previous embayment hydrodynamic and water quality modeling and historical eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Lewis Bay Estuarine System. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the Lewis Bay System and to reduce costs to the Towns of Barnstable and Yarmouth.

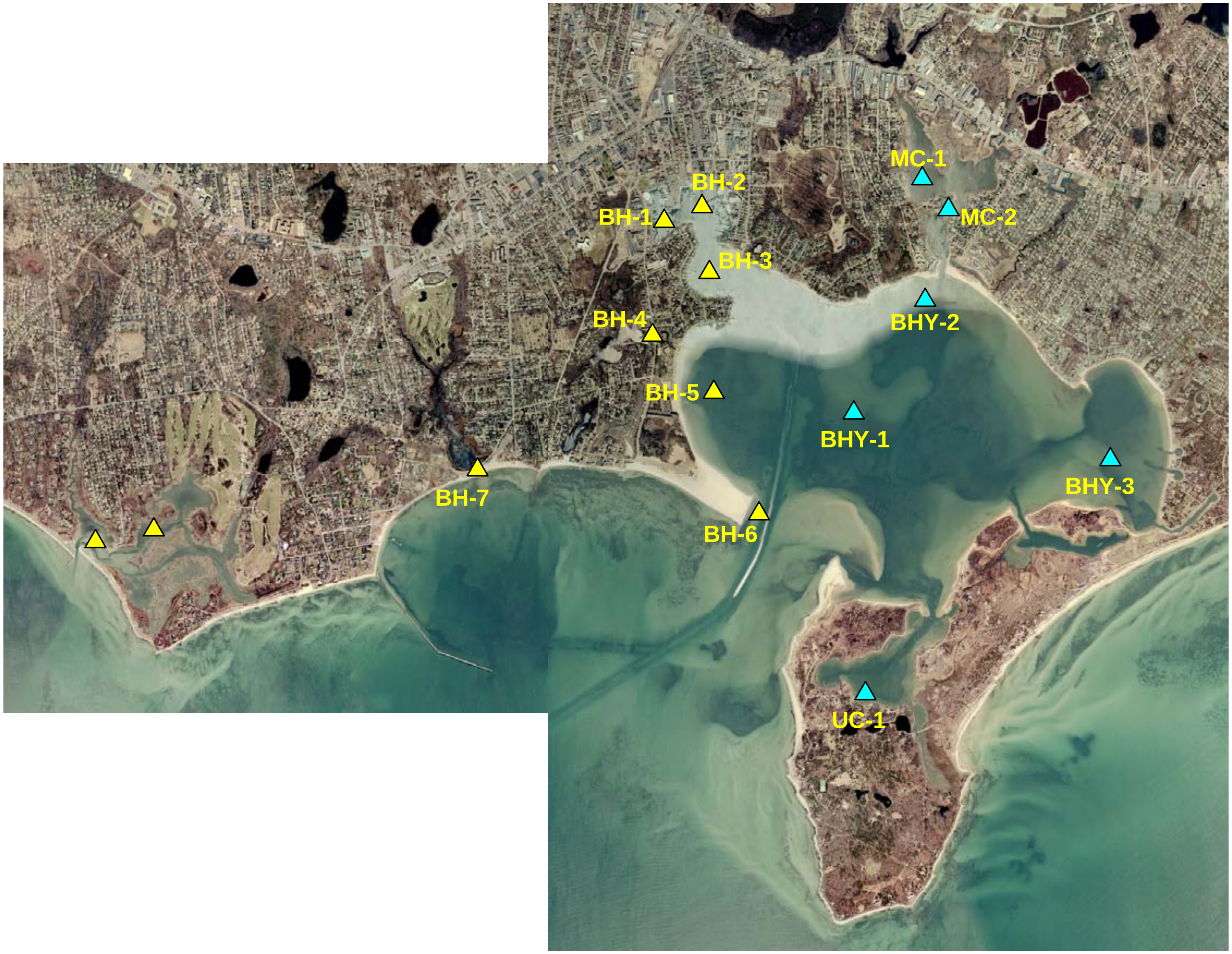


Figure II-1. Town of Barnstable/Yarmouth Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the Town and volunteers. Stream water quality stations sampled weekly by the MEP. Halls Creek along the eastern shore of Centerville Harbor will be assessed in a future MEP Technical Report on the Lewis Bay System.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). These USGS groundwater modelers were central to the development of the groundwater modeling approach used by the Estuaries Project. The USGS has a long history of developing regional models for the six-groundwater flow cells on Cape Cod. Through the years, advances in computing, lithologic information from well installations, water level monitoring, stream flow measurements, and reconstruction of glacial history have allowed the USGS to update and refine the groundwater models. The MODFLOW and MODPATH models utilized by the USGS organize and analyze the available data using up-to-date mathematical codes and create better tools to answer the wide variety of questions related to watershed delineation, surface water/groundwater interaction, groundwater travel time, and drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including the Lewis Bay embayment system located in Barnstable, Massachusetts. The Lewis Bay watershed is situated along the southern edge of Cape Cod and is bounded by Vineyard/Nantucket Sound.

In the present investigation, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the Lewis Bay embayment system under evaluation by the Project Team. The Lewis Bay estuarine system is a moderately complex estuary and includes wetland dominated portions at its northern edge. Further watershed modeling was undertaken to sub-divide the overall watershed to the Lewis Bay system into functional sub-units based upon: (a) defining inputs from contributing areas to each major portion within the embayment system, (b) defining contributing areas to major freshwater aquatic systems which generally attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands), and (c) defining 10 year time-of-travel distributions within each sub-watershed as a procedural check to gauge the potential mass of nitrogen from "new" development, which has not yet reached the receiving estuarine waters. The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in the Sagamore flow cell on Cape Cod. Model assumptions for calibration were matched to surface water inputs and flows from MEP stream flow measurements (2003 to 2004).

The relatively transmissive sand and gravel deposits that comprise most of Cape Cod create a hydrologic environment where watershed boundaries are usually better defined by elevation of the groundwater and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). Freshwater discharge to estuaries is usually composed of surface water inflow from streams, which receive much of their water from groundwater base flow, and direct groundwater discharge. For a given estuary, differentiating between these two water inputs and tracking the sources of nitrogen that they carry requires determination of the portion of the watershed that contributes directly to a stream and the portion of the groundwater system that discharge directly into an estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Lewis Bay system were delineated using a regional model of the Sagamore Lens flow cell (Walter and Whealan, 2005). The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, *et al.*, 2000) was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4 (Pollock, 2000), which uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies. This approach was used to determine the contributing areas to Lewis Bay system including sub-watersheds to Halls Creek, outer Lewis Bay (Hyannis Harbor), Stewarts Creek, Snows Creek, and Mill Creek and also to determine portions of recharged water that may flow through fresh water ponds and streams prior to discharging into coastal water bodies.

The Sagamore Flow Model grid consists of 246 rows, 365 columns and 20 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top 17 layers of the model extend to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft. The top of layer 8 resides at NGVD 29 with layers 1-7 stacked above and layers 8-20 below. Layer 18 has a thickness of 40 feet and extends to 140 feet below NGVD 29, while layer 19 extends to 240 feet below NGVD 29. The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics (up to 519 feet below NGVD 29); since bedrock is 300 to 400 feet below NGVD 29 in the Lewis Bay area the two lowest model layers were active in this area of the model. The rewetting capabilities of MODFLOW-2000, which allows drying and rewetting of model cells, was used to simulate the top of the water table, which varies in elevation depending on the location in the Lens.

The glacial sediments that comprise the aquifer of the Sagamore Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The sediments generally show a fining downward with sand and gravel deposits deposited in glaciofluvial (river) and near-shore glaciolacustrine (lake) environments underlain by fine sand, silt and clay deposited in deeper, lower-energy glaciolacustrine environments. Most groundwater flow in the aquifer occurs in shallower portions of the aquifer dominated by coarser-grained sand and gravel deposits. The Lewis Bay system watershed (including Snows and Stewarts Creeks) is generally split between the Barnstable Outwash Plain Deposits to the west and Harwich Outwash Plain Deposits to the east; the dividing line between the two deposits follows a line north from the northern portion of Mill Creek (Oldale, 1974a; Oldale, 1974b). The Halls Creek watershed is exclusively in the Barnstable Outwash Plain Deposits (Oldale, 1974a). Modeling and field measurements of contaminant transport at the MMR have shown that similar deposited materials are highly permeable (*e.g*., Masterson, *et al*., 1996). Given their high permeability, direct rainwater run-off is typically rather low for this type of watershed system. Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from USGS, local Town records and data from previous investigations. Final aquifer parameters in the groundwater model were determined through calibration to observed water levels and stream flows. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Towns and stream flow data collected in 1989-1990 as well as 2003.

The groundwater model simulates steady state, or long-term average, hydrologic conditions including a long-term average recharge rate of 27.25 inches/year and the pumping of public-supply wells at average annual withdrawal rates for the period 1995-2000 with a 15% consumptive loss. This recharge rate is based on the most recent USGS information. Large withdrawals of groundwater from pumping wells may have a significant influence on water tables and watershed boundaries and therefore the flow and distribution of nitrogen within the aquifer. After accounting for the consumptive loss and measured discharge at the Hyannis Water Pollution Control Facility (WPCF), water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within residential areas designated as using on-site septic systems.

III.3 LEWIS BAY SYSTEM AND HALLS CREEK CONTRIBUTORY AREAS

Newly revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the Lewis Bay embayment system, including the Mill Creek and Hyannis Inner Harbor sub-embayments, and Halls Creek estuary (Figure III-1). Model outputs of MEP watershed boundaries were "smoothed" to (a) correct for the grid spacing, (b) to enhance the accuracy of the characterization of the pond and coastal shorelines, (c) to include water table data in the lower regions of the watersheds near the coast (as available), and (d) to more closely match the sub-embayment segmentation of the tidal hydrodynamic model. The smoothing refinement was a collaborative effort between the USGS and the rest of the MEP Technical Team. The MEP sub-watershed delineation includes one 10 yr time of travel boundary. Overall, twenty-eight (28) sub-watershed areas, including eight freshwater ponds, were delineated within the Lewis Bay/Halls Creek study area.

Table III-1 provides the daily discharge volumes for various sub-watersheds as calculated from the groundwater model. These volumes were used to assist in the salinity calibration of the tidal hydrodynamic models and to determine hydrologic turnover in the lakes/ponds, as well as for comparison to measured surface water discharges. The overall estimated groundwater flow into the Lewis Bay system, including outer Lewis Bay and Stewarts Creek based on the MEP delineated watershed is 61,743 m3/d. The estimated groundwater flow into Hall Creek is 9,796 m3/d.

The delineations completed for the MEP project are the second watershed delineation completed in recent years for portions of the Lewis Bay system and Halls Creek. Figure III-2 compares the delineation completed under the current effort with the study area delineations completed by the Cape Cod Commission in 1998 as part of the Coastal Embayment Project (Eichner, *et al*., 1998). The delineation completed in 1998 was defined based on regional water table measurements collected from available wells over a number of years and normalized to average conditions. Delineations based on this previous effort were incorporated into the Commission's regulations through the Regional Policy Plan (CCC, 1996 & 2001).

The MEP watershed area for the Lewis Bay system as a whole is 9% larger (658 acres) than the 1995 CCC delineation. The differences are largely attributable to the inclusion of the outer Lewis Bay portion of the MEP delineation. The Halls Creek MEP watershed is 14% smaller than the 1995 CCC delineation; this is likely due to a better understanding of stream flow out of the Creek that were developed for the MEP (see Chapter IV). The MEP area calculations include corrections for portions of the pond and well sub-watersheds that discharge outside of the system, as well as accounting for differential flow from the Hyannis WPCF. Modeling completed by the USGS to assist the Wastewater Implementation Committee of Barnstable County helped the Town of Barnstable evaluate how much of the WPCF's flows are received by various ponds, public water supply wells, and estuary components in the study area. This effort was another benefit of the update of the regional groundwater model (Walter and Whealan, 2005). Interior sub-watersheds to individual freshwater ponds and public water supplies were not delineated in the CCC watersheds.

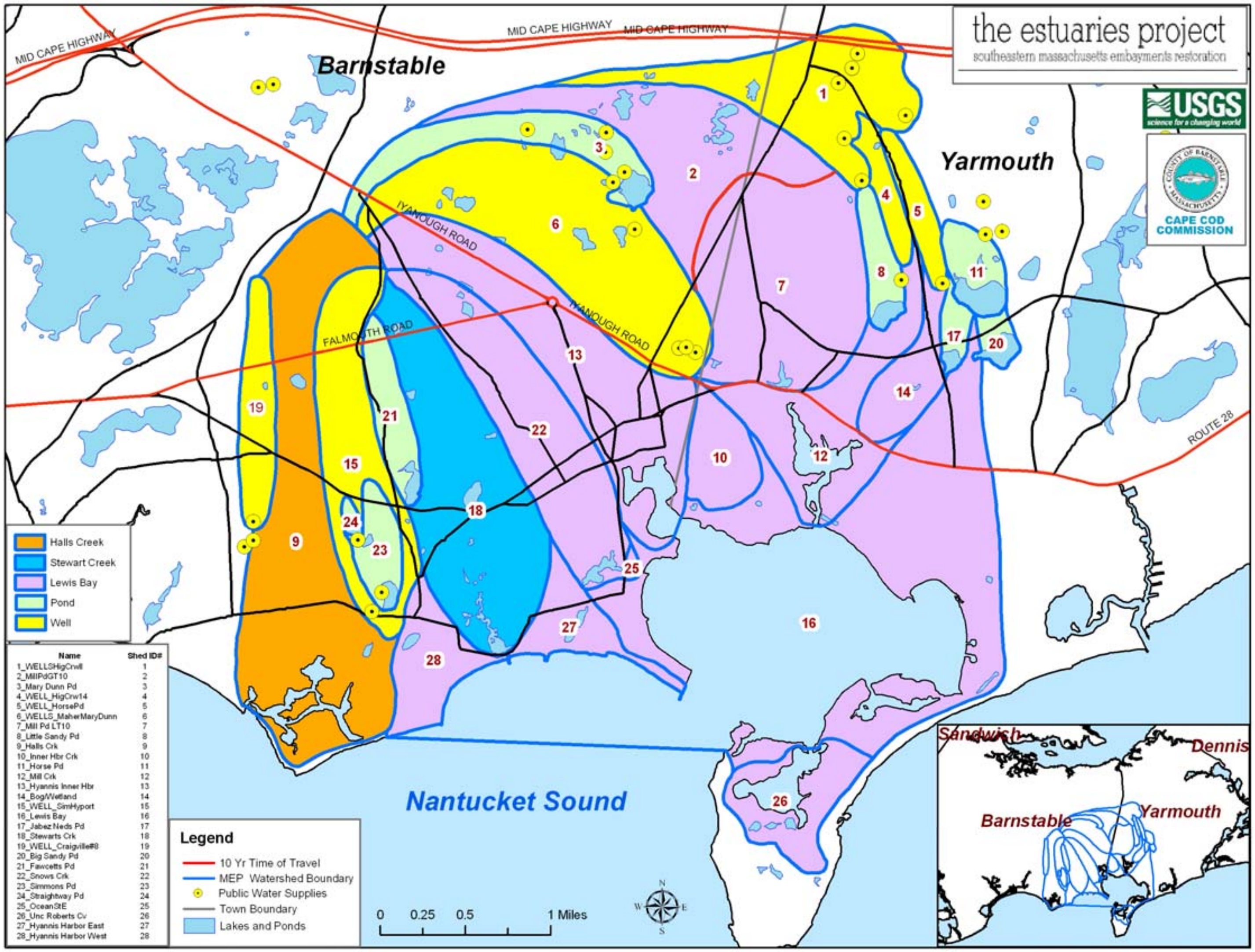


Figure III-1. Watershed and sub-watershed delineations for the Lewis Bay estuary system. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a "10" in the watershed names (above). Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI).

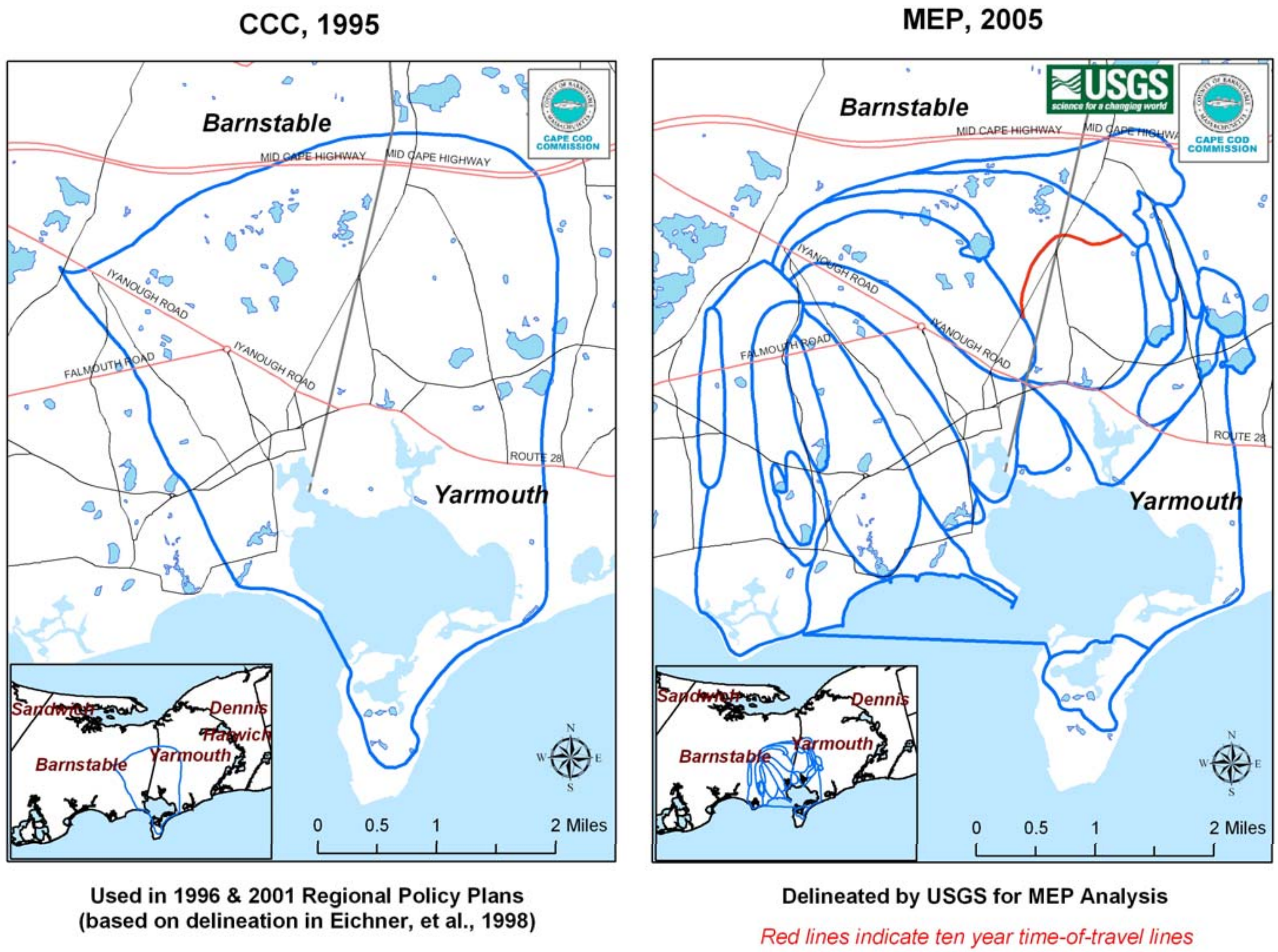


Figure III-2. Comparison of 1998 Cape Cod Commission and current Lewis Bay watershed and sub-watershed delineations.

Table III-1. Daily groundwater discharge to each of the sub-watersheds in the watershed to the Lewis Bay system estuary and Halls Creek estuary, as determined from the USGS groundwater model.

Watershed	#	Watershed Area (acres)	% contributing to Estuaries	Discharge	
				m^3/day	ft^3/day
WELLS_HigginsCrowell	1	455	49	1,698	59,972
Mill Pond GT10	2	511	100	3,920	138,443
Mary Dunn Pond	3	245	100	1,878	66,337
WELL_HigginsCrowell14	4	73	100	560	19,785
WELL_HorsePond	5	85	100	655	23,126
WELLS_MaherMaryDunn	6	801	100	6,144	216,973
Mill Pond LT10	7	693	100	5,322	187,934
Little Sandy Pond	8	89	100	686	24,210
Halls Creek	9	935	100	7,174	253,346
Inner Harbor Creek	10	147	100	1,126	39,762
Horse Pond	11	98	24	180	6,359
Mill Creek	12	359	100	2,752	97,189
Hyannis Inner Harbor	13	638	100	4,895	172,854
Bog/Wetland	14	148	100	1,137	40,139
WELL_SimmonsHyannisport	15	372	100	2,856	100,856
Lewis Bay	16	955	100	7,330	258,852
Jabez Neds Pond	17	44	100	334	11,805
Stewarts Creek	18	695	100	5,334	188,366
WELL_Craigville#8	19	84	50	324	11,444
Big Sandy Pond	20	40	27	83	2,938
Fawcetts Pond	21	127	100	977	34,501
Snows Creek	22	544	100	4,178	147,554
Simmons Pond	23	100	100	767	27,076
Straightway Pond	24	12	100	93	3,278
OceanStE	25	8	100	64	2,243
Uncle Roberts Cove	26	174	100	1,332	47,031
Hyannis Harbor East	27	141	100	1,121	39,584
Hyannis Harbor West	28	186	100	1,437	50,748
Hyannis WPC Facility*			100	6,435	227,257
TOTAL LEWIS BAY SYSTEM				61,743	2,180,432
TOTAL HALLS CREEK				9,796	345,931

*Hyannis Water Pollution Control Facility is assumed to discharge 1.7 million gallons per day based on average effluent discharge 2002-2006 (n=1,504)

Note: discharge volumes are based on 27.25 in of annual recharge over the watershed area; up-gradient ponds often discharge to numerous down-gradient sub-watersheds, percentage of outflow is determined by length of down-gradient shoreline going to each sub-watershed; totals may not exactly match columns sums due to apportionment of WPC facility flows. Measured flow at stream gage locations will not exactly match calculated whole watershed recharge values as ponds often sit on groundwater divides thereby splitting flows between different sub-watersheds.

The evolution of the watershed delineations for the Lewis Bay system and Halls Creek have allowed increasing accuracy as each new version adds new hydrologic data to that previously collected; the model allows all this data to be organized and to be brought into congruence with adjacent watersheds. The evaluation of older data and incorporation of new data during the development of the model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model used for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon the land-uses that are included/excluded within the contributing areas. Small errors in watershed area can result in large errors in loading if a large source is counted in or out. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the down-gradient estuary. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the aquatic systems and ultimately to the estuarine waters of the Lewis Bay system and Halls Creek (Section IV.1).

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

The MEP Technical Team includes technical staff from the Cape Cod Commission (CCC). In coordination with other MEP Technical Team members, CCC staff developed nitrogen-loading rates (Section IV.1) to the Lewis Bay embayment system and the Halls Creek estuary (Section III). The Lewis Bay and Halls Creek watersheds were sub-divided to define contributing areas to each of the major inland freshwater systems and to each major sub-embayment to Lewis Bay and sub-estuary to Halls Creek. Further sub-divisions were made to identify watershed areas where a nitrogen discharge reaches embayment waters in less than 10 years or greater than 10 years, although these are somewhat limited in this system due to all the up gradient wells and freshwater ponds. A total of 28 sub-watersheds were delineated for the Lewis Bay/Halls Creek estuary study area. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and each embayment/estuary (see Chapter III).

The initial task in the MEP land use analysis is to gage whether or not nitrogen discharges to the watershed have reached the estuary. This involves a temporal review of land use changes, the time of groundwater travel provided by the USGS watershed model, and review of data at natural collection points, such as streams and ponds. Evaluation and delineation of ten-year time of travel zones are a regular part of the watershed analysis, but for the Lewis Bay/Halls Creek study area only one ten-year travel line was delineated. This is the result of numerous up gradient ponds and wells intercepting flow and these resources being within 10 years of travel; more refined modeling would be required to better ascertain flow times within this complicated system. In one specific watershed (Mill Pond), most of the existing development is below the ten-year travel line and most of the area beyond the ten-year travel line is protected open space for Yarmouth's public water supply wells. MEP staff also reviewed land use development records for the age of developed properties in the watershed. Based on all these reviews, it was determined that Lewis Bay and Halls Creek are currently in balance with their watershed load. This finding is consistent with other MEP analysis where ten-year travel lines have been more prevalent. The overall result of the timing of development relative to groundwater travel times is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuaries (after accounting for natural attenuation, see below).

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 detailed studies is applied to other fractions of the watershed nutrient load. 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 Lewis Bay and Halls Creek estuary systems, the model used Town of Barnstable and Town of Yarmouth land-use data transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as parcel by parcel water use or groundwater monitoring wells). Determination of the nitrogen loads required obtaining watershed specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the "potential" or unattenuated nitrogen load to each receiving embayment, since attenuation during transport has not yet been included.

Natural attenuation of nitrogen during transport from land-to-sea (Section IV.2) within the Lewis Bay System watershed was determined based upon a site-specific study of stream flow from Mill Pond, Stewarts Creek, Chase Brook, Snows Creek, and a small stream near Hyannis Inner Harbor. Halls Creek had a site-specific study of stream flow in a stream leading into the estuarine portion of the Creek. Sub-watersheds to these various portions allowed comparisons between field collected data from the streams and ponds and estimates from the nitrogen-loading sub-model. Attenuation through the ponds were conservatively assumed to equal 50% based on available monitoring of selected Cape Cod lakes; calculations for individual ponds were also determined. Stream flow and associated surface water attenuation is included in the MEP's nitrogen attenuation and freshwater flow investigation, presented in Section IV.2.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. In the present effort, measurements were made of attenuation in Mary Dunn Pond, Fawcetts Pond, Big Sandy Pond, Horse Pond, Jabez Neds Pond, Little Sandy Pond and in the stream complexes mentioned above. Simmons and Straightway Ponds have sub-watershed level land use data, but do not have water quality monitoring data, so nitrogen attenuation in these systems cannot be compared to site-specific data. However, if smaller aquatic features that have not been included in this MEP analysis were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (~10%) overestimated given the distribution of nitrogen sources within the watershed. Based upon these considerations, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate

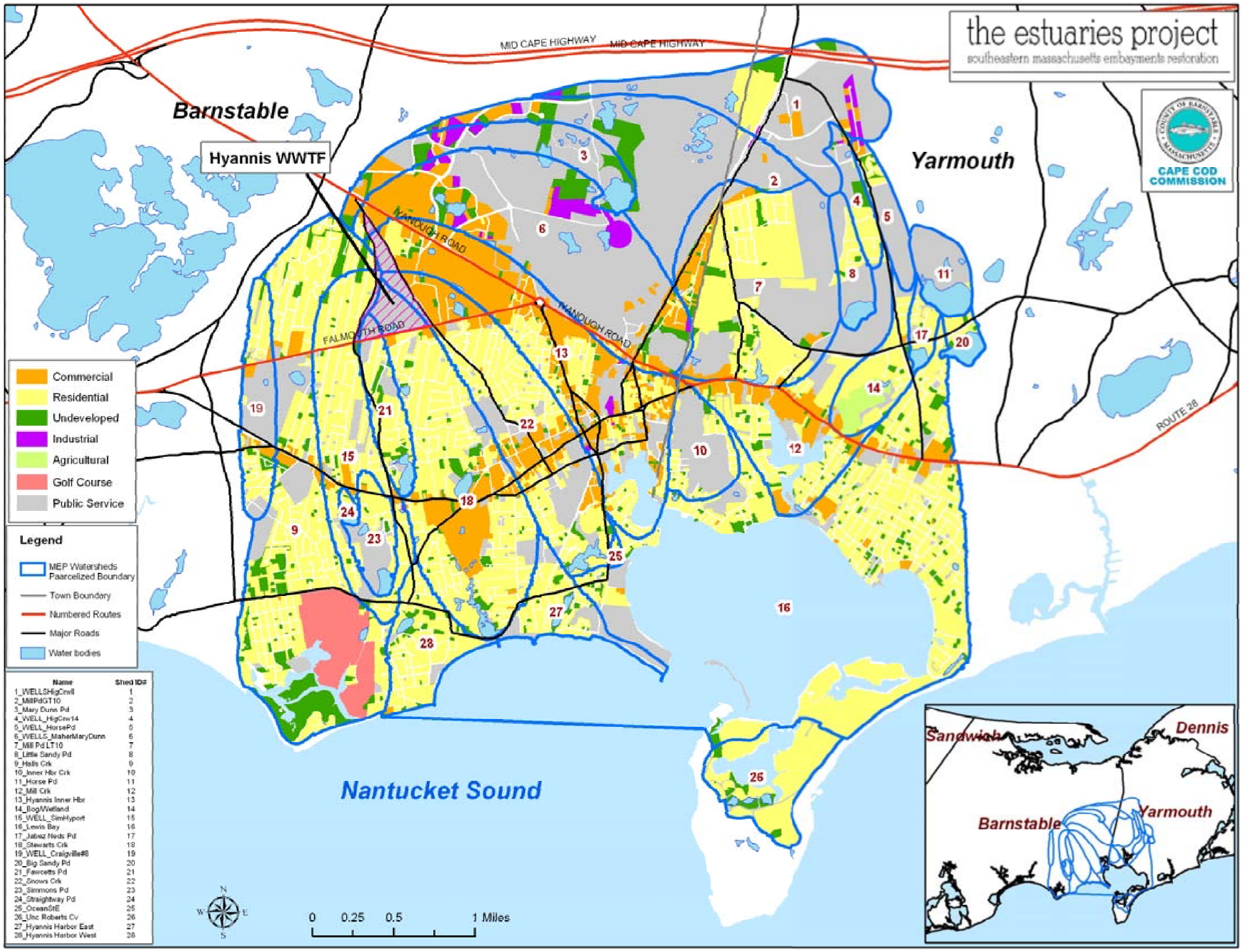


Figure IV-1. Land-use in the Lewis Bay and Halls Creek system watersheds. The Halls Creek system watershed is completely contained within the Town of Barnstable, while the Lewis Bay system watershed is split between the Town of Barnstable and the Town of Yarmouth. Land use classifications are based on assessors' records provided by the towns.

of nitrogen loading for the eight sub-watersheds that directly discharge groundwater to the estuary without flowing through one of these interim measuring points. Internal nitrogen recycling was also determined throughout the tidal reaches of the Lewis Bay and Halls Creek Estuarine Systems; 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

Estuaries Project staff obtained Town of Barnstable digital parcel and tax assessors data from the town Geographic Information Systems Department and the Town of Yarmouth parcel and assessor data via the Town Department of Public Works. Digital parcels and land use/assessors data for both towns are from 2004. These land use databases contain traditional information regarding land use classifications (MADOR, 2002) plus additional information developed by the Towns. The parcel data and assessors' databases were combined for the MEP analysis by using the Cape Cod Commission Geographic Information System (GIS).

Figure IV-1 shows the land uses within the Lewis Bay and Halls Creek estuary watershed areas. Land uses in the study area are grouped into nine land use categories: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) undeveloped, 6) agricultural, 7) golf course, 8) public service/government, including road rights-of-way, and 9) freshwater features (e.g. ponds and streams). These land use categories, except the freshwater features, are aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2002). These categories are common to each town in the watershed. “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 Lewis Bay System watershed, the predominant land use based on area is public service/government, which accounts for 42% of the overall watershed area (Figure IV-2). Most of this area is due to the Hyannis Airport and the protected public water supply areas in both Barnstable and Yarmouth. In the individual sub-watersheds, public service/government land uses vary between 25 and 55% of the sub-watershed areas. Residential land uses are the second highest percentage (35%) of the Lewis Bay system watershed area and are the predominant parcel type in the watershed, accounting for 74% of the parcels in the system watershed. Single-family residences (MADOR land use code 101) are 84% of the residential parcels and single-family residences are 63% of the residential land area. In the individual sub-watersheds, residential land uses vary between 19 and 52% of the sub-watershed areas. After residential land use, commercial land use is the third highest percentage (12%) of the Lewis Bay system watershed area and occupies 37% of the Hyannis Inner Harbor sub-watershed. Undeveloped land uses are 8% of the system watershed.

In the overall Halls Creek System watershed, the predominant land use based on area is residential, which accounts for 52% of the overall watershed area (Figure IV-2). Residential land uses are also the predominant parcel type, accounting for 89% of the parcels in the watershed. Single-family residences (MADOR land use code 101) are 89% of the residential land area and 97% of the residential parcels. Public service/government land uses are the second highest percentage (25%) of the Halls Creek watershed area and developable and golf course are tied for third with 10% each. Commercial land uses are 2% of the watershed area.

In order to estimate wastewater flows within the Lewis Bay study area, the Cape Cod Commission obtained parcel-by-parcel water use information from the Towns of Barnstable and Yarmouth. The Barnstable water use data includes information from the Centerville, Osterville, Marstons Mills (COMM) Water District and the Town of Barnstable Water Supply Division (WSD). The Yarmouth water use data was provided by the Town of Yarmouth Department of Public Works. The water use data from both Barnstable water suppliers, as well as from Yarmouth, is from 2001 through 2005. The Town of Barnstable Department of Public Works also provided a listing of parcels that are connected to the municipal sewer system and the Hyannis Water Pollution Control Facility (WPCF), as well as effluent quantities and total nitrogen concentration data for January 2002 through November 2006. Three private wastewater treatment facilities also discharge within the Yarmouth portion of the watershed to Lewis Bay; effluent flow and total nitrogen data was supplied by MassDEP. Three alternative, denitrifying septic systems also discharge within the study area; the Barnstable County Department of Health and the Environment supplied effluent total nitrogen data for these systems. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the measured water-use, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2).

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts, decennial census data 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 applied on a parcel-by-parcel basis within a watershed, where annual water meter data is linked to assessors parcel information using GIS techniques. The parcel specific water use data is converted to septic system nitrogen discharges (to the receiving aquatic systems) by adjusting for consumptive use (e.g. irrigation) and applying a wastewater nitrogen concentration. The water use approach focuses on the nitrogen load, which reaches the aquatic receptors down gradient in the aquifer.

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). Down gradient studies of septic system plumes indicate that further nitrogen loss during aquifer transport is negligible (Robertson et al. 1991, DeSimone and Howes 1996).

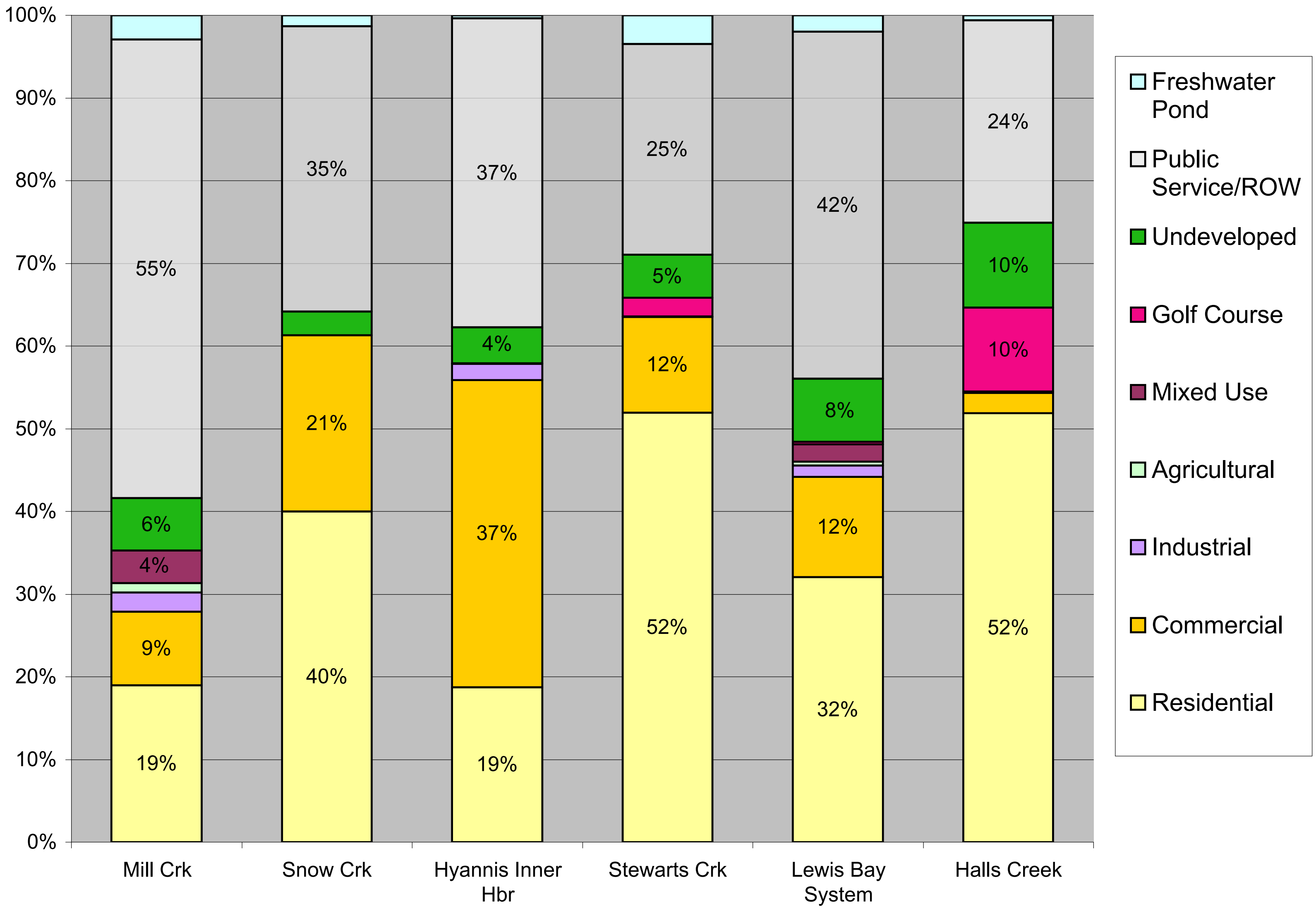


Figure IV-2. Distribution of land-uses within the major sub-watersheds and whole watershed to the Lewis Bay estuary system and the watershed to Halls Creek. Only percentages greater than or equal to 4% are shown.

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

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

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

Overall, the MEP water use approach for determining septic system nitrogen loads has been both calibrated and validated in a variety of watershed settings. The approach: (a) is consistent with a suite of studies on per capita nitrogen loads from septic systems in sandy 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) and the reasonableness of the freshwater attenuation (Section IV.2) add additional weight to the nitrogen loading coefficients used in the MEP analyses and a variety of other MEP embayments. While the MEP septic system nitrogen load is the best estimate possible, to the extent that it may underestimate the nitrogen load from this source reaching receiving waters provides a safety factor relative to other higher loads that are generally used in regulatory situations. The lower concentration results in slightly higher amounts of nitrogen mitigation (estimated at 1% to 5%)) needed to lower embayment nitrogen levels to a nitrogen target (e.g. nitrogen threshold, cf. Section VIII). The additional nitrogen removal is not proportional to the septic system nitrogen level, but is related to the how the septic system nitrogen mass compares to the nitrogen loads from all other sources that reach the estuary (i.e. attenuated loads).

In order to provide an independent validation of the average residential water use within the Lewis Bay System and Halls Creek watersheds, MEP staff reviewed US Census population values for the Towns of Barnstable and Yarmouth. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. Based on data collected during the 2000 US Census, average occupancy within Barnstable is 2.44 people per housing unit, while year-round occupancy of available housing units is 78%. Average water use for single-family residences with municipal water accounts in the Lewis Bay/Halls Creek study area is 175 gpd. If this flow is multiplied by 0.9 to account for consumptive use, the watershed average is 158 gpd. If this flow is then divided by 55 gpd, the average estimated occupancy in the study area is 2.87 people per household.

In most previously completed MEP studies, average population and average water use have generally agreed fairly well. Since review of water use in the Lewis Bay/Halls Creek study area suggests that on average occupancy rates are higher, MEP staff reviewed more refined US Census information, 1990 Census information, and data from previous MEP reviews, and water use information for each parcel within the watershed. Besides reviewing data on town and state levels, the US Census also develops information for smaller areas (i.e., tracts and block groups). Portions of four Census tracts are contained within the watershed to Lewis Bay; year 2000 Census residential occupancy rates in the tracts range from 2.26 to 2.45 people per house. Average occupancy for these tracts reported for the 1990 Census range from 2.12 to 2.49 people per house. While these occupancies suggest that the area is given to a fairly wide range of readings, these occupancies are less than the occupancy expected based on water use.

MEP staff then reviewed the average water uses measured in the sub-watersheds of the Lewis Bay/Halls Creek study area. While the overall average for single-family residences (SFRs) is 175 gpd, averages in the sub-watersheds varied widely with a range between 119 and 246 gpd. Review of individual SFR water uses within sub-watershed ranged as high as 3,767 gpd, but even this use was consistent across five years of data. The standard deviation among all the watershed averages is 41 gpd; the population-based estimate of wastewater flow is within one standard deviation of the measured estimate of wastewater flow.

In addition to the above analyses, MEP staff encountered a similar situation with the Centerville River water use data (Howes, et al., 2006). In that analysis, which also involved Barnstable water use, a similar relationship of water use being seemingly too high for the 2000 Census population estimates was also encountered. In that case, further analysis by staff also found that the difference was larger than usually found but within a reasonable range, especially if a conservative factoring of summer population was added.

At the outset of the MEP, project staff decided to utilize the water use approach for determining residential wastewater generation by septic systems because of the inherent difficulty in accurately gauging actual occupancy in areas impacted by seasonal population fluctuations such as most of Cape Cod. Estimates of summer populations on Cape Cod derived from a number of approaches (*e.g.*, traffic counts, garbage generation, sewer use) suggest average population increases from two to three times year-round residential populations measured by the US Census. While land use characteristics in the Lewis Bay and Halls Creek sub-watersheds may be unlikely to see summer population increases at the upper end of regional estimates, a doubling of the watershed occupancy for four months would be sufficient to increase the average annual water use based on Title 5 to 171 gpd, which is approximately the same as the average measured flow in the watershed. The above analysis suggests that additional analysis of water uses within the Lewis Bay and Halls Creek watersheds should be considered, but review of the water uses on the parcel, Census tract, and watershed scales do not suggest that there are any consistent inaccuracies. Given all the above analysis and the difficulty in accurately gauging seasonal population fluctuations, MEP staff decided to continue to use the Lewis Bay and Halls Creek watershed-specific water uses without any additional factors. Additionally, the MEP used the average water use for the residential parcels without water use data and for the 851 additional residential parcels included in the buildout analysis that will not be connected to the Hyannis municipal sewer system.

Although water use information exists for 89% of the 8,085 developed parcels in the Lewis Bay/Halls Creek study area, there are 899 parcels that 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 do not have a listed account in the water use databases. Of the 899 parcels, 77% of them (696) are classified as residential with 580 of these being classified as single-family residences (land use code 101). The remaining 23% of the parcels are commercial and industrial properties (300s and 400s land use codes, respectively). MEP staff used current water use to develop a watershed-specific water use estimate for the residential uses that were assumed to utilize private wells. Commercial and industrial properties assumed to have private wells were assigned a water use based on percentage of parcel building coverage and average water uses for commercial properties and industrial properties in the Lewis Bay/Halls Creek study area.

Hyannis Water Pollution Control Facility

The Hyannis Water Pollution Control Facility (WPCF) is located at the intersection of Route 28 and Bearses Way. The facility operators use a sequence of treatment processes to denitrify effluent prior to its discharge in sand beds located on site. The Town of Barnstable is currently in the process of completing review of a Final Environmental Impact Report for its Facilities Plan that will provide a strategy for operation and upgrades to the WPCF and its sewer system over the next 20 years (Stearns and Wheler, 2007).

Effluent flow and total nitrogen concentration data was provided to MEP staff by staff at the Town of Barnstable Department of Public Works. This data covers the period from January 2002 through November 2006. Total flow at the WPCF is generally consistent across the years reviewed (Figure IV-3). Median total nitrogen effluent concentrations are a bit more variable, but tend to fluctuate within a 4 to 8 mg/l range. The available dataset includes 430 readings of effluent total nitrogen concentrations and 1,504 readings of daily effluent quantity. Average effluent quantity during this period is 1.7 million gallons per day (MGD), while total nitrogen concentration averages 5.51 mg/l. The total nitrogen concentration has a standard deviation of 1.98 mg/l and a range of 0.02 to 13.1 mg/l. Median concentration is 5.20 mg/l. For the purposes of the watershed nitrogen loading modeling, MEP staff used an effluent flow of 1.7 MGD and an effluent total nitrogen concentration of 5.51 mg/l. These factors result in an annual current nitrogen load of 12,947 kg/yr from the WPCF.

In order to assess whether there was significant unaccounted for wastewater flows in the sewer collection system, MEP staff also reviewed water flows for all properties listed in available coverages as being connected to the WPCF. This review found a number of parcels that were unaccounted for in the original matching of water use and parcel databases. CCC GIS staff worked to identify these parcels and accounted for their flow in the nitrogen-loading model. This review also identified a few parcels with exceptionally high average water use rates; rates were reviewed for consistency and generally the high average was the result of one exceptionally high year. Water uses for these properties were adjusted to an average of the four remaining years in the watershed nitrogen-loading model.

The WPCF is located in the midst of a number of watersheds. USGS completed additional groundwater modeling for the Town of Barnstable through a grant from the Barnstable County Wastewater Implementation Committee. This groundwater modeling utilized the same model used for the MEP watershed delineations (Walter and Whealan, 2005). The USGS used the model to quantitatively determine which wells, streams, ponds, and estuaries received groundwater flow from effluent discharged at the WPCF. Through the grant, the USGS provided the town with a number of flow scenarios. MEP staff utilized a 1.7 MGD discharge scenario to distribute effluent flow and nitrogen loads from the WPCF to the respective sub-watersheds listed in Table IV-1.

Table IV-1. Nitrogen Loads from the Wastewater Treatment Facilities to Estuary Watersheds in the Lewis Bay/Halls Creek Study Area

Sub-watershed	Nitrogen Load (kg/y)		
	Hyannis WPCF	Private WWTF	TOTAL
Mill Creek		237	237
Mill Pond		172	172
Hyannis Inner Harbor	627		627
Snows Creek	4,219		4,219
Stewarts Creek Total	7,112		7,112
Halls Creek	988		988
TOTAL	12,947	409	13,356

Loads based on monitoring data from facilities within each watershed or from the Hyannis WPCF, which discharges to multiple watersheds

Yarmouth Private Wastewater Treatment Facilities

Three private wastewater treatment facilities exist in the Yarmouth portion of the Lewis Bay watershed: Mayflower Place, Buck Island Village, and The Cove. MEP staff obtained effluent flow and total nitrogen discharge concentrations for 2004 through 2006 from MassDEP based on discharge permit reporting (B. Dudley, personal communication). Buck Island and the Cove discharge within the Mill Creek sub-watershed, while Mayflower Place discharges within the Mill Pond sub-watershed.

From the available dataset, Mayflower Place has an average effluent discharge of 11,519 gpd with an average effluent total nitrogen concentration of 10.96 mg/l (n=34). Buck Island Village has an average effluent discharge of 9,046 gpd with an average effluent total nitrogen concentration of 8.63 mg/l (n=35). The Cove has an average effluent discharge of 11,804 gpd with an average effluent total nitrogen concentration of 8.14 mg/l (n=35). MEP staff determined monthly nitrogen loads for each facility and summed these on an annual basis. The annual nitrogen load from each facility was determined based on the average of three years of annual loads: Mayflower Place, 171.9 kg/y; Buck Island, 106.8 kg/y; and The Cove, 129.9 kg/y. These loads are summarized by sub-watershed in Table IV-1.

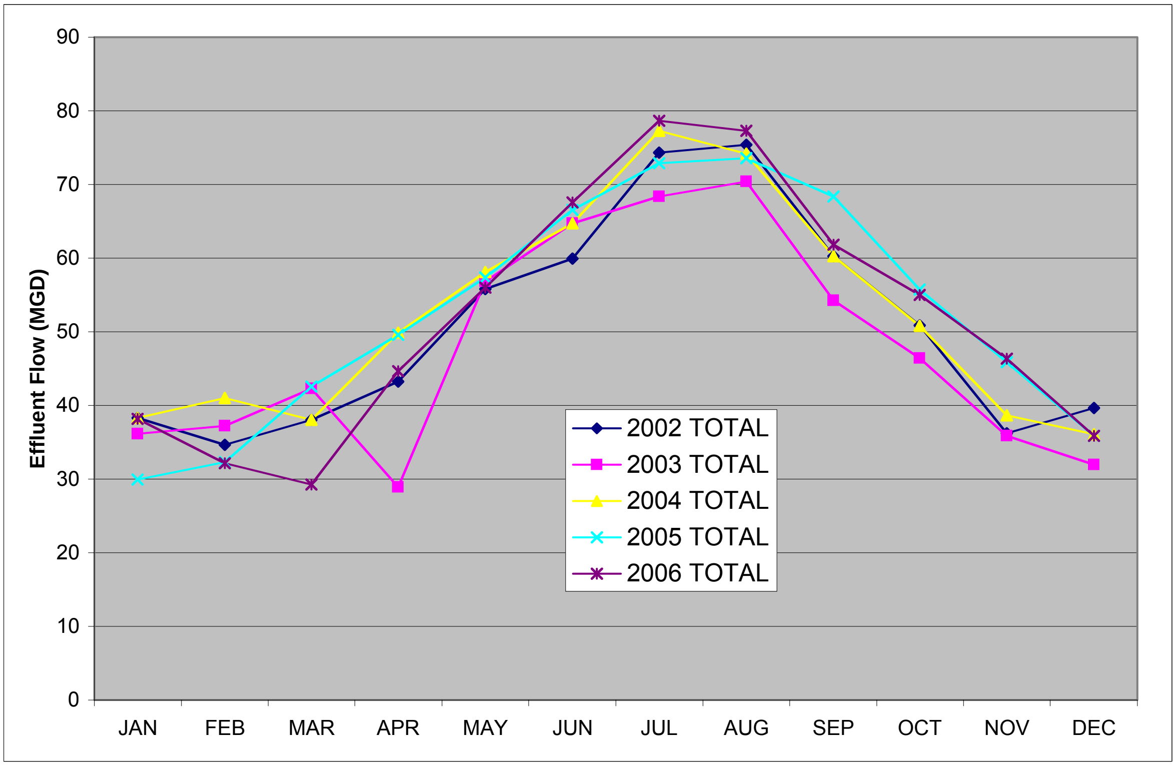
Alternative Septic Systems

Three alternative septic systems are identified in Barnstable County Department of Health and the Environment tracking system as being located within the Lewis Bay/Halls Creek study area (S. Rask, personal communication, 1/07). Total nitrogen concentrations were available from 41 samples collected from these three systems between 2000 and 2006. The average total nitrogen concentration (22.23 mg/l) times a 0.9 consumptive use factor was used for these three properties instead of the 23.63 wastewater coefficient used for properties with standard Title 5 septic systems.

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 lawns being the predominant source within this category. In order to add this source to the nitrogen loading model for the Lewis Bay system, MEP staff reviewed available information about residential lawn fertilizing practices and incorporated site-specific information to determine nitrogen loading from large tracks of turf in the watershed. MEP staff contacted the staff at appropriate organizations regarding the following large turf areas: the Hyannisport Club and Twin Brooks golf courses and playing fields for the Barnstable Public Schools. Cranberry bog nitrogen loading was determined based on previous studies conducted in southeastern Massachusetts.

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 per 1,000 sq. ft., c) each lawn is 5000 sq. ft., and d) only 25% of the nitrogen applied reaches the groundwater (leaching rate). Because many of these assumptions had not been rigorously reviewed in over a decade, the MEP Technical Staff undertook an assessment of lawn fertilizer application rates and a review of leaching rates for inclusion in the Watershed Nitrogen Loading Sub-Model.



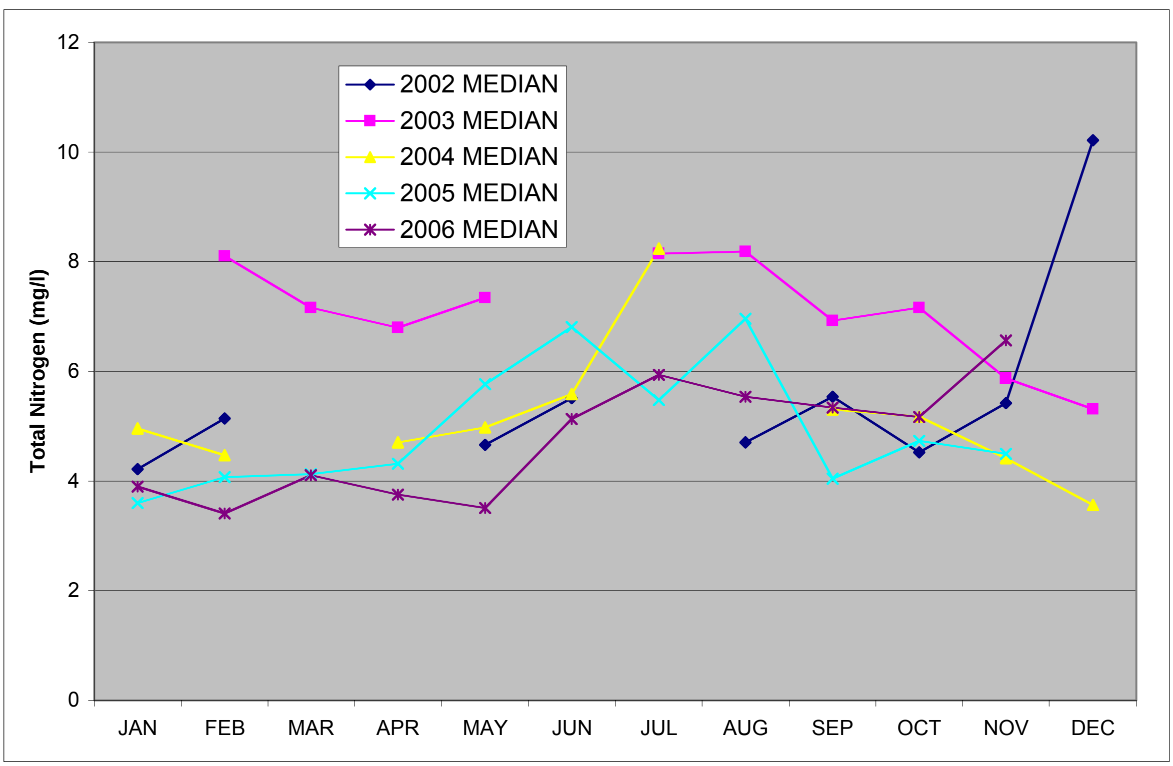


Figure IV-3. Total effluent discharge and median effluent total nitrogen concentration at the Hyannis Water Pollution Control Facility (2002-2006)

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. The assessment accounted for proximity to fresh ponds and embayments. Based upon ~300 interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sq. ft., 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a leaching rate of 20% results in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors are used in the MEP nitrogen loading calculations. It is likely that this still represents a conservative estimate of nitrogen load from residential lawns. It should be noted that professionally maintained lawns were found to have the higher rate of fertilizer application and hence higher estimated loss to groundwater of 3 lb/lawn/yr.

MEP staff contacted Mark Egan and Kevin Young at the Hyannisport Club and Twin Brooks Golf Course, respectively, to obtain current information about fertilizer application rates at the two golf courses. Golf courses usually have different fertilizer application rates for different turf areas, usually higher annual application rates for tees and greens (~3-4 pounds per 1,000 square feet) and lower rates for fairways and roughs (~2-3.5 pounds per 1,000 square feet). At the Hyannisport Club, Mr. Egan reported the following annual nitrogen application rates (in lbs/1,000 ft2) for the various turf areas: greens, 3.0; tees, 2.75; fairways, 3.75, and rough, 3.25. Mr. Young reported the following annual nitrogen application rates (in lbs/1,000 ft2) for the various turf areas at the Twin Brooks Golf Course: greens, 2.75; tees, 3.5; fairways, 3.0, and rough, 2.75.

As has been done in all MEP reviews, MEP staff reviewed the layout of the Hyannisport Club and Twin Brooks Golf Course from aerial photographs, classified the turf types, and assigned these areas to the appropriate sub-watersheds. The nitrogen application rates were then applied to these areas and a load was calculated. The Hyannisport Club is located within the Halls Creek sub-watershed, while the Twin Brooks Golf Course is located within the Stewarts Creek sub-watershed.

MEP staff also contacted Lee Saarkinnen of the Barnstable Public Schools. Mr. Saarkinnen indicated that turf at the Barnstable Public Schools playing fields have an annual nitrogen application rate of 0.75 lbs per acre. These playing fields are located at the Barnstable Middle and High School. Field areas were determined based on review of aerial photographs. A portion of these fields is located within the Halls Creek sub-watershed.

Cranberry bog fertilizer application rate and percent nitrogen attenuation in the bogs is based on the only annual study of nutrient cycling and loss from cranberry agriculture that has been conducted in southeastern Massachusetts (Howes and Teal, 1995). Only the bog loses measurable nitrogen, the forested upland releases only very low amounts. For the watershed nitrogen loading analysis, the areas of active bog surface are based on review of aerial photographs for properties classified as cranberry bogs in the town-supplied land use classifications. Cranberry bogs are located within the Chase Brook sub-watershed.

Nitrogen Loading Input Factors: Other

The 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). The recharge rate for natural areas and lawn areas is the same as utilized in the MEP-USGS groundwater modeling effort (Section III). Factors used in the MEP nitrogen loading analysis for the Lewis Bay watershed are summarized in Table IV-2.

The impervious surface factors were also used to add nitrogen load from the runways, taxiways, and tarmac at the Hyannis Airport. The area of these surfaces was determined from aerial photographs and the corresponding loads were added to the nitrogen-loading model. Loads from impervious surfaces at the airport are within the sub-watersheds to Mill Pond and Hyannis Inner Harbor.

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 resulting “parcelized” watersheds to Lewis Bay and Halls Creek are shown in Figure IV-4.

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 Lewis Bay estuary. The assignment effort was undertaken to better define sub-estuary loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Following the assignment of all parcels, sub-watershed modules were generated for each of the 28 sub-watersheds summarizing water use, parcel area, frequency, sewer connections, private wells, and road area. The individual sub-watershed modules were then integrated to create a Lewis Bay Watershed and a Hall Creek Nitrogen Loading module with summaries for each of the individual sub-embayments and sub-estuaries. The sub-embayments represent the functional embayment 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 Lewis Bay/Halls Creek study area, the major types of nitrogen loads are: wastewater (e.g., septic systems), wastewater treatment facilities, fertilizer, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-3). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-5 a-f). 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.

Table IV-2. Primary Nitrogen Loading Factors used in the Lewis Bay MEP analyses. General factors are from MEP modeling evaluation (Howes and Ramsey 2001). Site-specific factors are derived from Barnstable and Yarmouth data. *Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.

Nitrogen Concentrations:	mg/l	Recharge Rates:	in/yr	
Road Run-off	1.5	Impervious Surfaces	40	
Roof Run-off	0.75	Natural and Lawn Areas	27.25	
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:		
Natural Area Recharge	0.072	Existing developed residential parcels wo/water accounts and buildout residential parcels:	175 gpd	
Wastewater Coefficient	23.63			
Hyannis Water Pollution Control Facility				
Effluent Flow (million gallons per day)	1.7			
Effluent Total Nitrogen concentration (mg/l)	5.51	Existing developed parcels w/water accounts:	Measured annual water use	
Fertilizers:		Commercial and Industrial Buildings wo/WU and buildout additions		
Average Residential Lawn Size (sq ft)*	5,000	Commercial	BAR	YAR
Residential Watershed Nitrogen Rate (lbs/lawn)*	1.08	Wastewater flow (gpd/1,000 ft2 of building):	52	146
Cranberry Bogs nitrogen application (lbs/ac)	31	Building coverage:	20%	13%
Cranberry Bogs nitrogen attenuation	34%	Industrial	BAR	YAR
Nitrogen Fertilizer Rate for golf courses, cemeteries, and public parks determined from site-specific information		Wastewater flow (gpd/1,000 ft2 of building):	5	32
Average Building Size from watershed data (sq ft)	1,175	Building coverage:	15%	20%

Since groundwater outflow from a pond can enter more than one down gradient sub-watershed, the length of shoreline on the down gradient side of the pond was used to apportion the pond-attenuated nitrogen load to respective down gradient watersheds. The apportionment was based on the percentage of discharging shoreline bordering each down gradient sub-watershed. So for example, Mary Dunn Pond has a down gradient shoreline of 942 feet; 72% of that shoreline discharges into the Mill Pond GT10 sub watershed (watershed 2 in Figure IV-1) and 28% discharges to the Maher/Mary Dunn combined wellfield sub-watershed (watershed 6). The attenuated nitrogen load discharging from Lake Wequaquet is divided among these sub-watersheds based on the percentage of the down-gradient shoreline.

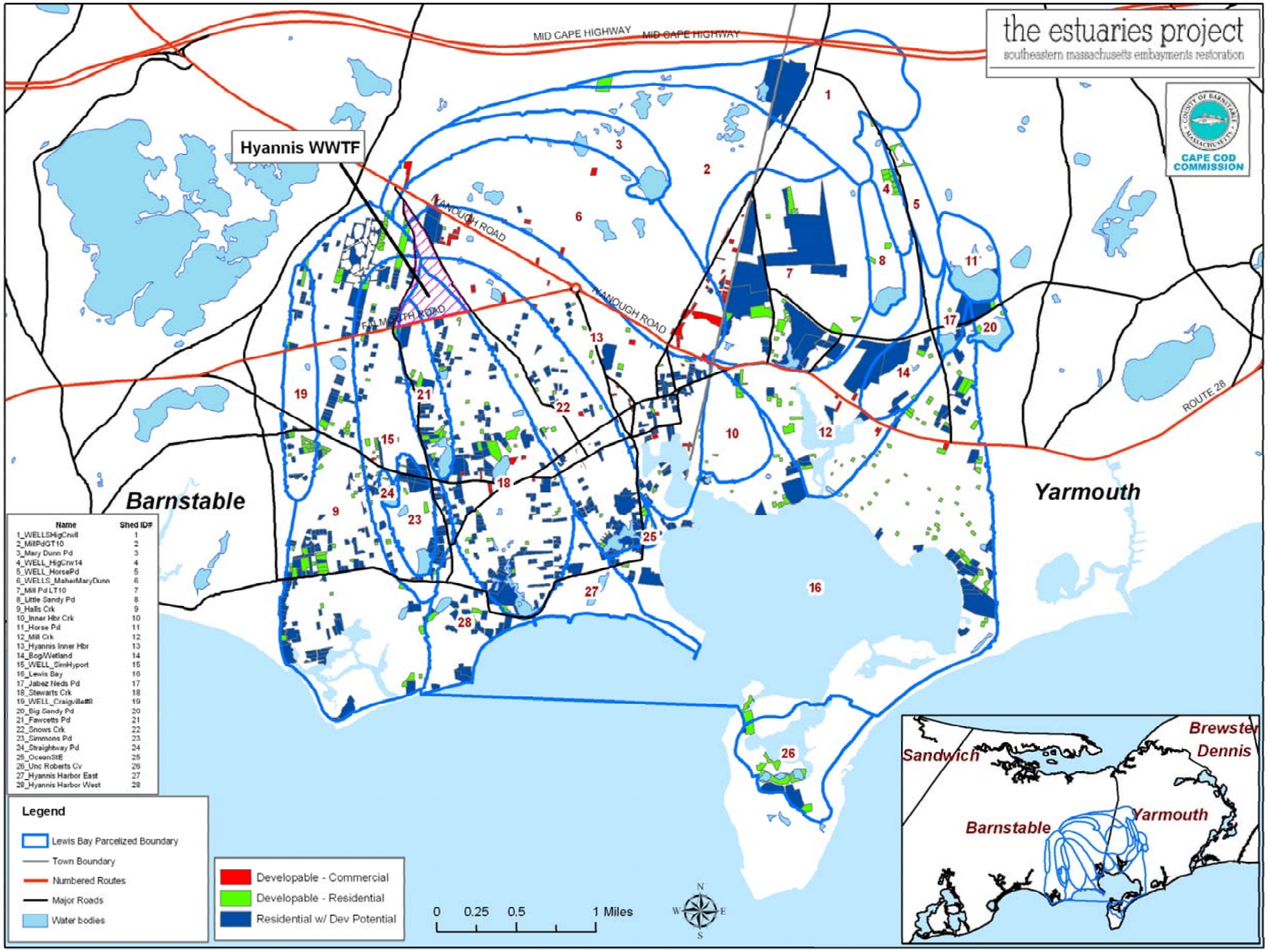
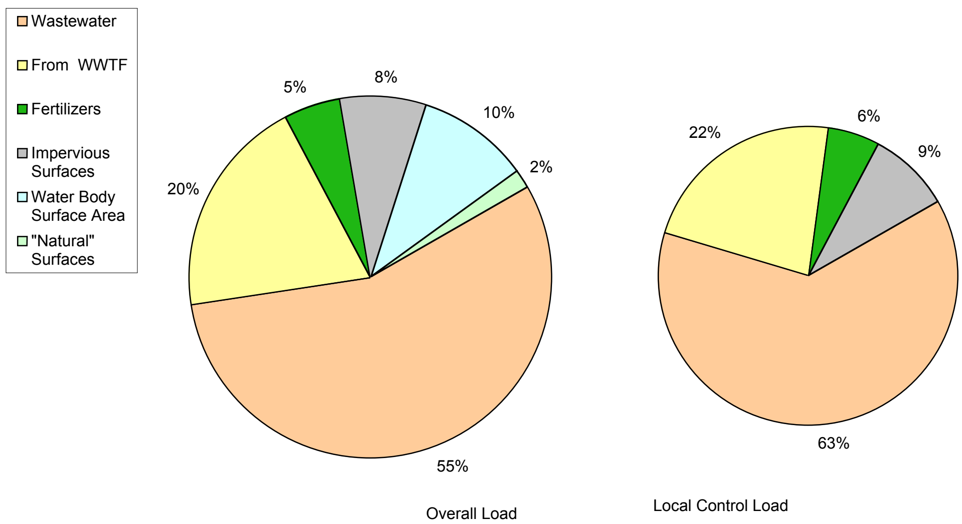


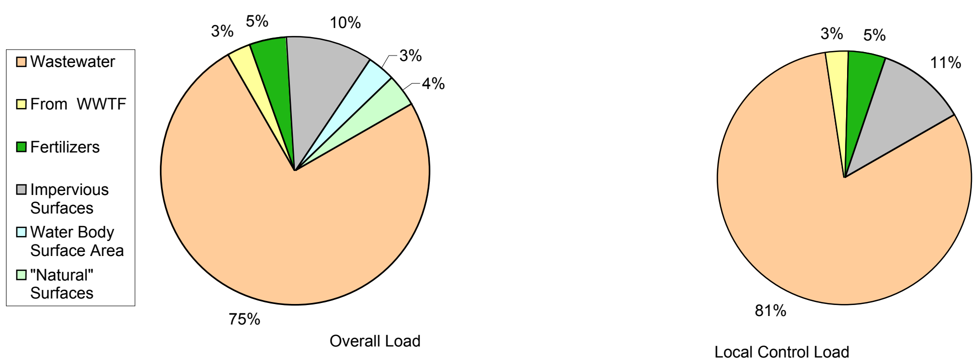
Figure IV-4. Parcels, Parcelized Watersheds, and Developable Parcels in the Lewis Bay and Halls Creek watersheds.

Table IV-3. Lewis Bay and Halls Creek Nitrogen Loads. Attenuation of Lewis Bay and Halls Creek system nitrogen loads occurs as nitrogen moves through up-gradient ponds and streams during transport to the estuary. All values are kg N yr^{-1}.

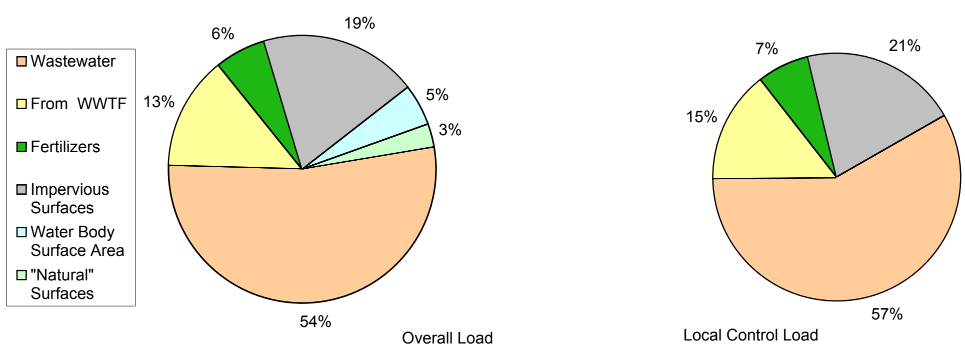
		Lewis Bay and Halls Crk N Loads by Input (kg/y):								*Present N Loads*			*Buildout N Loads*		
Watershed Name	**Watershed ID#**	**Wastewater**	**From WWTF**	**Fertilizers**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**% of Pond Outflow**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Lewis Bay System Total		34909	12367	3084	4937	6100	1107	17237		62504		56327	79742		71230
Lewis Bay Estuary TOTAL		26417	5255	2051	3881	5958	956	11547		44517		39067	56065		48466
Stewarts Creek TOTAL		6170	7112	782	749	125	106	5649		15045		14318	20694		19781
Hyannis Harbor Estuary surface deposition															
Lewis Bay Estuary TOTAL		26417	5255	2051	3881	5958	956	11547		44517		39067	56065		48466
Lewis Bay Estuary surface deposition						4930				4930		4930	4930		4930
Uncle Roberts Cove Estuary surface deposition						277				277		277	277		277
Mill Creek Total	12, CB, MP	10727	409	652	1499	476	553	5747		14315		11527	20062		16139
Mill Pond Total	MP	4309	172	163	1072	164	385	3118		6266	30%	4251	9385	30%	6372
Chase Brook	CB	1412	0	289	106	52	52	393		1911	30%	1221	2304	30%	1484
Mill Creek Estuary surface deposition						229				229		229	229		229
Hyannis Inner Harbor Total	6,13	2496	627	290	885	241	128	1015		4668		4661	5683		5671
Hyannis Inner Harbor Estuary surface deposition						231				231		231	231		231
Snows Creek Total	22,25	2559	4219	366	621	34	77	3342		7875		5517	11217		7859
Stewarts Creek TOTAL		6170	7112	782	749	125	106	5649		15045		14318	20694		19781
Stewarts Creek Estuary surface deposition						86				86		86	86		86
Halls Creek Total		6221	988	1554	731	269	160	1516		9924		9063	11440		10513
Halls Creek Stream Total	21, SP	648	988	63	77	39	19	98		1834	30%	973	1932	30%	1005
Simmons Pond Total	SP	515	0	52	64	33	17	39		680	50%	319	718	50%	335
Halls Creek Estuary surface deposition						230				230		230	230		230



a. Lewis Bay System Overall

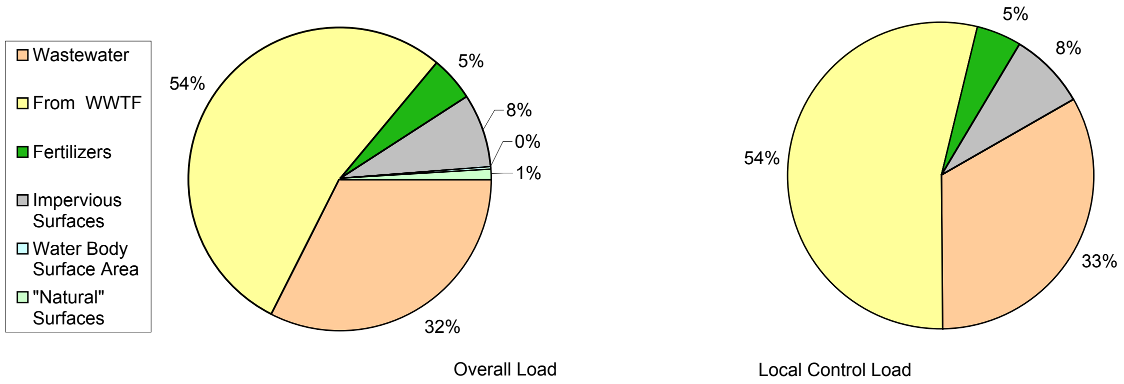


b. Mill Creek subwatershed

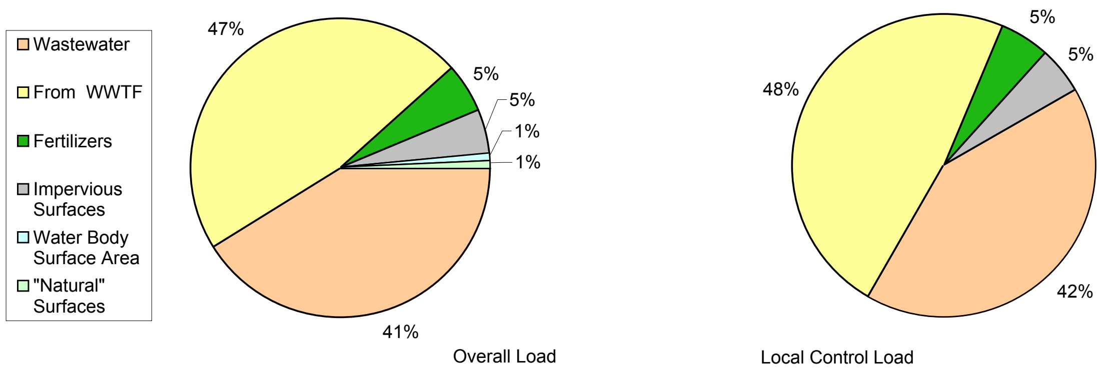


c. Hyannis Inner Harbor subwatershed

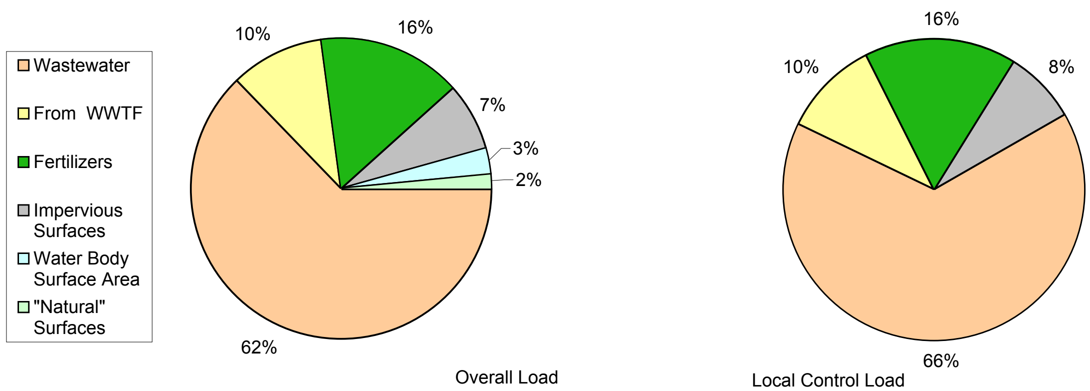
Figure IV-5 (a-c). Land use-specific unattenuated nitrogen load (by percent) to the (a) overall Lewis Bay System watershed, (b) Mill Creek sub-watershed, and (c) Hyannis Inner Harbor sub-watershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.



d. Snows Creek subwatershed



e. Stewarts Creek System Overall



f. Halls Creek System Overall

Figure IV-5 (d-f). Land use-specific unattenuated nitrogen load (by percent) to the (d) Snows Creek sub-watershed, (e) Stewarts Creek sub-watershed and (f) the Halls Creek system. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.

Freshwater Pond Nitrogen Loads

Freshwater ponds on Cape Cod are generally kettle hole depressions that intercept the surrounding groundwater table revealing what some call “windows on the aquifer.” Groundwater typically flows into the pond along the up gradient shoreline, then lake water flows back into the groundwater system along the down gradient shoreline. Occasionally a Cape Cod pond will also have a stream outlet or herring run that also acts as a discharge point. Since the nitrogen loads flow into the pond with the groundwater, the relatively more productive pond ecosystems incorporate some of the nitrogen, retain some nitrogen in the sediments, and change the nitrogen among its various oxidized and reduced forms. As result of these interactions, some of the nitrogen is removed from the watershed system, mostly through burial in the sediments and denitrification that returns it to the atmosphere. Following these reductions, the remaining (reduced or attenuated) loads flow back into the groundwater system along the down gradient side of the pond or through a stream outlet and eventual discharge into the down gradient embayment. The nitrogen load summary in Table IV-3 includes both the unattenuated (nitrogen load to each sub watershed) and attenuated nitrogen loads.

Pond nitrogen attenuation in freshwater ponds has generally been found to be at least 50% in MEP analyses, so the watershed model contains a conservative attenuation rate of 50%. However, in some cases, if sufficient monitoring information is available, a pond-specific attenuation rate is incorporated into the watershed nitrogen loading modeling (Three Bays MEP Report, 2005). Detailed studies of other southeastern Massachusetts freshwater systems including Ashumet Pond (AFCEE, 2000) and Agawam/Wankinco River Nitrogen Discharges (CDM, 2001) have also supported a 50% attenuation factor. In order to estimate nitrogen attenuation in the ponds, physical and chemical data for each pond is reviewed. Available bathymetric information is reviewed relative to measured pond temperature profiles to determine whether an epilimnion (*i.e.*, well mixed, homothermic, upper portion of the water column) exists in each pond. Bathymetric information is necessary to develop a residence or turnover time and complete an estimate of nitrogen attenuation. In the Lewis Bay and Halls Creek watersheds, bathymetric information is available for only Mary Dunn Pond; in order to complete nitrogen attenuation estimates, MEP staff estimated the volumes based on maximum depths that had been measured during PALS Snapshot sampling. Given these ponds relatively small areas, it would be likely that none are deep enough to develop strong temperature stratification and samples from all depths generally can be used for determining average nitrogen concentrations. Deepest samples must be checked for potential impact by sediment regeneration of nitrogen, especially if low oxygen conditions occur.

In MEP analyses, available nitrogen concentrations from individual ponds are reviewed to establish whether sediment regeneration is a significant factor in a pond and, if not, the entire volume of the pond is used to determine a turnover time. Turnover time is how long it takes the recharge from the up gradient watershed to completely exchange the water in the pond or, in the case of a thermally stratified pond, exchange just the epilimnion. The total mass of nitrogen in the pond or epilimnion is adjusted using the pond turnover time to determine the annual nitrogen load returned to the aquifer through the down gradient shoreline. This mass is then compared to the nitrogen load coming from the pond’s watershed to determine the nitrogen attenuation factor for the pond. Monitoring of ponds within the Lewis Bay and Halls Creek system watersheds is insufficient to support use of a factor different than the standard 50% attenuation.

The standard attenuation assumption for the ponds in the Lewis Bay watershed was checked through the use of pond water quality information collected from the annual Cape Cod Pond and Lake Stewardship (PALS) water quality snapshot. The PALS Snapshot is a collaborative Cape Cod Commission/SMAST Program that allows trained, citizen volunteers of each of the 15 Cape Cod towns to collect pond samples in August and September using a standard protocol. Snapshot samples have been collected every year between 2001 and 2005. The standard protocol for the Snapshot includes field collection of dissolved oxygen and temperature profiles, Secchi disk depth readings and water samples at various depths depending on the total depth of the pond. PALS Snapshot data is available in the Lewis Bay watershed for the following ponds: Mary Dunn, Fawcetts, Big Sandy, Horse, Jabez Neds, and Little Sandy. Data is not available for Simmons or Straightway Ponds. Water samples were analyzed at the SMAST laboratory for total nitrogen, total phosphorus, chlorophyll *a*, alkalinity, and pH. Table IV-4 presents the turnover times and attenuation factors for the ponds in the Lewis Bay and Halls Creek watersheds.

Table IV-4 also summarizes the pond attenuation estimates calculated from land-use modeled nitrogen inflow loads and nitrogen loads recharged to the down gradient aquifer or to outflow streams from each pond based on pond characteristics and measured nitrogen levels. Nitrogen attenuation within the ponds was approximately 65% based on the results of attenuation calculations for Mary Dunn Pond where bathymetry data was available. However, a caveat to the attenuation estimates is that they are based upon nitrogen outflow loads from water column samples collected at one time during the year, that are not necessarily representative of the annual nitrogen loads that are transferred down gradient, and there are only a small number of samples for review.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development within the study area watershed. For the Lewis Bay/Halls Creek modeling, MEP staff consulted with Town of Barnstable and Town of Yarmouth planners to determine the factors that would be used in the assessment (Patty Daley, Tom Broadrick, and Terry Sylvia, personal communications). The buildout analysis was complicated by accounting for the Hyannis Growth Incentive Zone (GIZ) and future connections to the Hyannis Water Pollution Control Facility. MEP staff first reviewed the development potential of each property based on existing zoning within both Yarmouth and Barnstable. The buildout procedure used, and generally completed for MEP analyses, is to evaluate town zoning to determine minimum lot sizes in each of the zoning districts, including overlay districts (*e.g.*, water resource protection districts). Larger lots are subdivided by the minimum lot size to determine the total number of new lots and existing developed properties are reviewed for additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence. MEP staff also included additional development on residential parcels that are classified as developable residential (state class land use codes 130 and 131) but are less than the minimum lot size and are greater than 5,000 square feet. These parcels are assigned one residence in the buildout; 5,000 square feet is a common minimum buildable lot size in Cape Cod town regulations. Properties classified by the Barnstable and Yarmouth assessors as "undevelopable" (e.g., codes 132, 392, and 442) were not assigned any development at buildout. Commercially developable properties were not subdivided; the area of each parcel and the factors in Table IV-3 were used to determine a wastewater flow for these properties. MEP staff then met individually with town planning staff to review the initial buildout analysis and modified the results based on their local knowledge of other site constraints. All the parcels included in the buildout assessment of the Lewis Bay and Halls Creek watersheds are shown in Figure IV-4.

Table IV-4. Nitrogen attenuation by Freshwater Ponds in the Lewis Bay and Halls Creek watersheds based upon 2001 through 2005 Cape Cod Pond and Lakes Stewardship (PALS) program sampling. These data were collected to provide a site-specific check on nitrogen attenuation by these systems. The MEP Linked N Model for Lewis Bay and Halls Creek uses a standard value of 50% for all the pond systems.

Pond	PALS ID	Area acres	Maximum Depth m	Overall turnover time yrs	TN samples for Attenuation calculation	N Load Attenuation %
Mary Dunn	BA-646	18.0	1.7	0.2	3	65%
Fawcetts	BA-748	11.9	1.3	No Bathymetric Info	4	Not calculated due to lack of bathymetry
Simmons	BA-789	7.2			0	
Straightway	BA-771	4.3			0	
Big Sandy	YA-711	19.4	4.0		4	
Horse	YA-692	30.3	3.5		8	
Jabez Neds	YA-716	7.5	3.1		2	
Little Sandy	YA-700	14.0	8.0		4	
					Mean	65%
					std dev	n/a

Data sources: all areas from CCC GIS; Max Depth from Cape Cod PALS monitoring; TN concentrations for attenuation calculations from annual PALS Snapshot provided by SMAST lab; Volume for turnover time calculations for Mary Dunn Pond from MADFW bathymetric maps (www.mass.gov/dfwele/dfw/dfw_pond.htm);

Because of the sewer system in Hyannis has the potential to remove wastewater nitrogen loads from the individual sites and move this load to the WPCF site, the next step was to identify properties that are already connected to the municipal sewer system or are included within the Hyannis GIZ. Based on discussion with Town of Barnstable staff, it was determined that any additional development within the GIZ would be connected to the municipal sewer system. Based on this analysis, buildout within the watershed would add 1.25 MGD of flow to the WPCF; bringing the total WPCF flow at buildout to 2.95 MGD. Nitrogen loads from the WPCF under buildout conditions are based on the buildout flow and the current effluent total nitrogen concentration of 5.51 mg/l. This analysis does not include any additional flows from Areas of Concern identified through the town Facilities Plan; additional scenario analyses would be necessary to explore these impacts. Distribution of the estimated buildout flows and nitrogen loads from the WPCF to various sub-watersheds are based on a USGS scenario of 2.0 MGD discharge at the WPCF; this scenario is the closest flow to the estimated buildout flow of the scenarios completed by the USGS for the town by the Barnstable County Wastewater Implementation Committee modeling grant.

Overall, each additional residential, commercial, or industrial property added at buildout is assigned nitrogen loads for wastewater (if not connected to the WPCF), fertilizer, and impervious surfaces. Wastewater loads from parcels using a septic system for wastewater treatment are assigned within the watershed that contains the parcel, while those connected to the WPCF do not have wastewater loads on site. Cumulative unattenuated buildout loads are indicated in a separate column in Table IV-3. Buildout additions within the overall Lewis Bay System watershed will increase the unattenuated loading rate by 28% and within the Halls Creek watershed by 15%.

Scenarios

At the request of Town of Barnstable and Town of Yarmouth staff, MEP staff completed six additional scenarios. Through a current Comprehensive Wastewater Management Planning process, the Town of Yarmouth delineated a potential sewer district (Figure IV-6). Both town staffs agreed to the following scenarios: A) collection of wastewater within the proposed district and removal of wastewater loads from Lewis Bay watershed, B) collection of wastewater within the proposed district and treatment and discharge at the Hyannis WPCF, and C) collection of wastewater within the proposed district, treatment at the Hyannis WPCF, and discharge within an abandoned bog system to the east of Cape Cod Hospital. Wastewater flows were developed under both current and buildout conditions.

MEP staff developed a separate “sewershed” module for the proposed district, which cuts across six sub-watersheds. The sewershed module contains all the properties in the proposed district according to their current sub-watershed assignments. Just as in the standard nitrogen loading analysis, staff determined water use for all developed properties within the sewershed and potential future water use at buildout based on a review of developable land and additional development on existing developed properties. Total existing wastewater load within the whole sewershed is 7,792 kg/yr and buildout will add 2,486 kg/yr.

Under scenario A, the existing and buildout loads from the sewershed are removed from the respective sub-watersheds. Under scenario B, wastewater flows are assumed to be discharged at the Hyannis WPCF and redistributed to various sub-watersheds based on the analyses described above. Under scenario C, the WPCF-treated effluent from the sewershed is discharged at the abandoned bogs in the Inner Harbor Creek sub-watershed. The scenario C loads receive an additional 30% attenuation from the bog system. Overall impacts on all loads are shown in Table IV-5.

Table IV-5. Existing and buildout unattenuated nitrogen loading changes due to proposed scenarios for wastewater discharge from Town of Yarmouth potential sewer service area. Scenario A removes the wastewater nitrogen loads from the Lewis Bay watershed. Scenario B treats the wastewater at the Hyannis Water Pollution Control Facility. Scenario C treats the wastewater at the WPCF and discharges it at abandoned bogs to the east of Cape Cod Hospital. All values are kg N yr^{-1}.

		SCENARIO A		SCENARIO B		SCENARIO C	
		Remove YAR sewer		YAR Sewer to Hyannis WPCF		YAR Sewer to Hyannis WPCF/Bog discharge	
Watershed Name	Wtrshd ID#	Existing	BO	Existing	BO	Existing	BO
Lewis Bay	16	-1769	-243				
Inner Harbor Creek	10	-824	-23			1788	389
Mill Creek	12	-4250	-1716				
Mill Pond LT10	7	-145	-410				
Bog/Wetland	14	-13	-76				
Hyannis Inner Harbor	13	-791	-17	87	19		
Snows Creek	22			583	127		
Stewarts Creek	18			925	202		
Fawcetts Pond	21			57	12		
Halls Creek Stream Total	21, SP			136	30		
SCENARIO TOTAL		-7792	-2486	1788	389	1788	389
NET LOAD TO LEWIS BAY		-7792	-2486	-6141	-2127	-6004	-2097
NET LOAD TO HALLS CREEK				136	30		

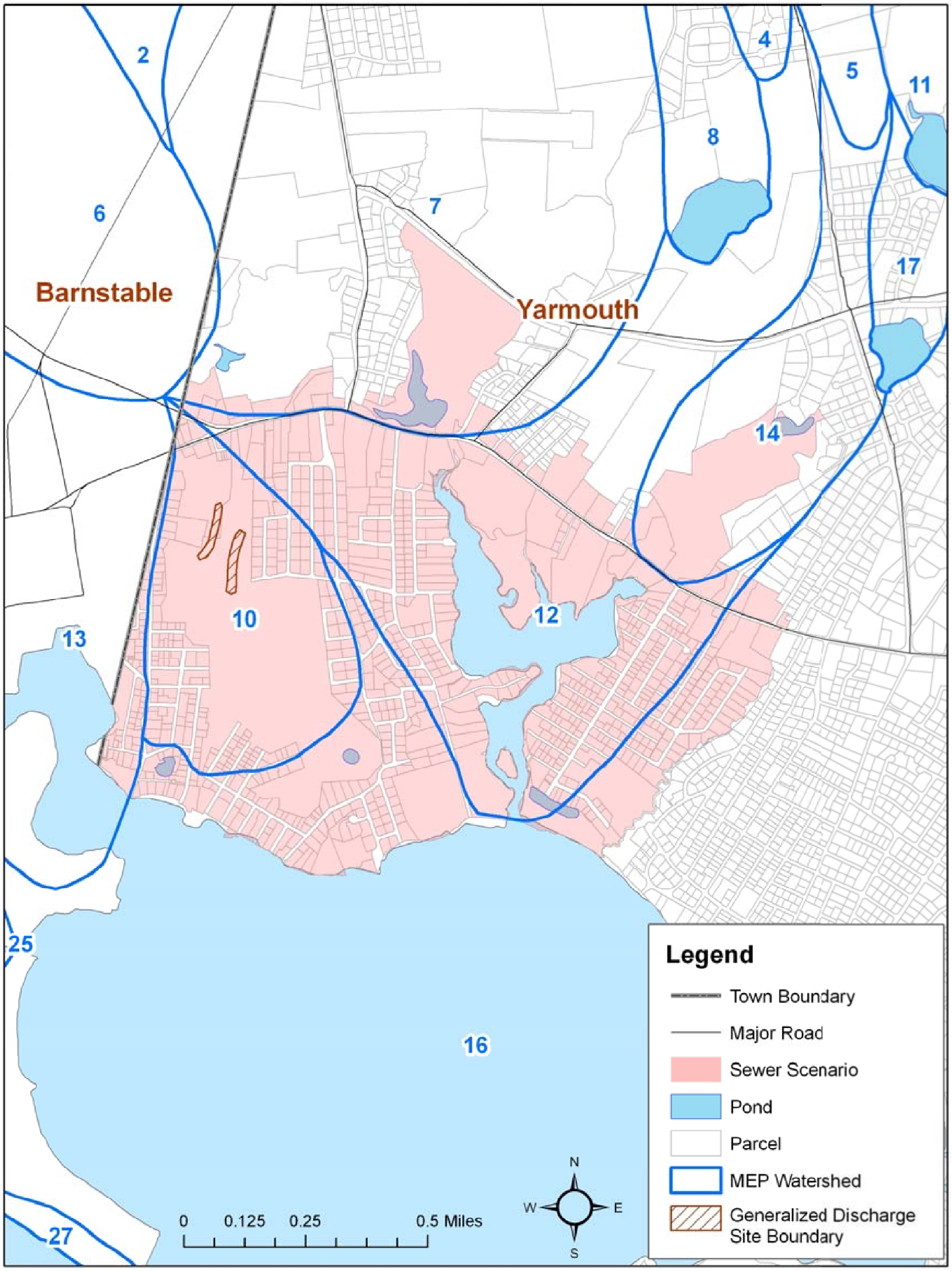


Figure IV-6. Lewis Bay Sewer Scenario Collection Area. Potential sewer collection area is shown in pink. Potential Scenario C discharge areas are shown based on Barnstable Facilities Plan (2007).

IV.2 Attenuation of nitrogen in surface water transport

IV.2.1 Background and Purpose

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out, sewering analysis, enhanced flushing, pond/wetland restoration for natural attenuation, etc.) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the sub-watersheds of the Lewis Bay System (inclusive of Hyannis Inner Harbor and Mill Creek estuarine reaches) being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1). If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such as the developed region of the Lewis Bay System watershed). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. However, in most watersheds in southeastern Massachusetts, nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the case of the Lewis Bay embayment system watersheds, a portion of the freshwater flow and transported nitrogen passes through several surface water systems (Hall’s Creek, Stewart’s Creek, Snow’s Creek, Creek to Hyannis Inner Harbor from Hospital Bog, Stream from Mill Pond to the estuarine reach of Mill Creek, Chase Brook to Mill Creek, Bumps River, stream from Long Pond, stream from Lake Elizabeth) prior to entering the estuary, producing the opportunity for significant nitrogen attenuation.

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

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP Approach. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the perimeter of the embayment system in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). These additional site-specific studies were conducted in the 6 major surface water flow systems in the watershed to Lewis Bay, 1) Halls Creek discharging to the outermost portion of Lewis Bay, 2) Stewart's Creek discharging to outer Lewis Bay, 3) Snow's Creek discharging to Inner Lewis Bay, 4) Creek from Hospital Bog discharging to Hyannis Inner Harbor, 5) Stream from Mill Pond discharging to the estuarine reach of Mill Creek and 6) Chase Brook discharging to the estuarine reach of Mill Creek (Figure IV-7).

Quantification of watershed based nitrogen attenuation is contingent upon being able to compare nitrogen load to the embayment system directly measured in freshwater stream flow (or in tidal marshes, net tidal outflow) to nitrogen load as derived from the detailed land use analysis (Section IV.1). Measurement of the flow and nutrient load associated with the freshwater streams discharging to the estuary provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up gradient from the various gauging sites. Flow and nitrogen load were measured at the gages in each freshwater stream site for between 15 and 26 months of record depending on the stream gauging location (Figures IV-8 to IV-12). During each study period, velocity profiles were completed on each river every month to two months. The summation of the products of stream subsection areas of the stream cross-section and the respective measured velocities represent the computation of instantaneous stream flow (Q).

Figure IV-7. Location of Stream gages (red symbols) in the Lewis Bay embayment system.

Determination of stream flow at each gage was calculated and based on the measured values obtained for stream cross sectional area and velocity. Stream discharge was represented by the summation of individual discharge calculations for each stream subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire stream cross section were not averaged and then applied to the total stream cross sectional area.

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

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

where by:

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

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

Periodic measurement of flows over the entire stream gage deployment period allowed for the development of a stage-discharge relationship (rating curve) that could be used to obtain flow volumes from the detailed record of stage measured by the continuously recording stream gages. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given river. These hourly stages values where then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. In the case of tidal influence on stream stage, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of strictly freshwater flow. The two low tide stage values for any given day were averaged and the average stage value for a given day was then entered into the stage – discharge relation in order to compute daily flow. A complete annual record of stream flow (365 days) was generated for the surface water discharges flowing into the Lewis Bay embayment system.

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

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Halls Creek to Outer portion of Lewis Bay

Simmons Pond, located up gradient of the Halls Creek gage site is a small freshwater pond and unlike many of the freshwater ponds on Cape Cod, this pond has stream outflow rather than discharging solely to the aquifer along its down-gradient shore. This stream outflow, Halls Creek, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands and streambed associated with Halls Creek. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to Halls Creek above the gage site and the measured annual discharge of nitrogen to the tidal portion of the Halls Creek marsh system, Figure IV-7.

At the Halls Creek gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the freshwater portion of the Halls Creek-Halls Creek marsh estuarine system that carries the flows and associated nitrogen load to the outer portion of Lewis Bay. As portions of the Halls Creek system are tidally influenced, the gage was located above the saltwater reach such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average low tide salinity was determined to be 0.1 ppt. Therefore, the gage location was deemed acceptable for making freshwater flow measurements. Calibration of the gage was checked monthly. The gage on Halls Creek was installed on April 24, 2003 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued until November 8, 2004 for a total deployment of 18 months.

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Halls Creek site based upon these flow measurements and measured water levels at the gage site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the estuarine portion of the Halls Creek Marsh system flowing into the outer portion of Lewis Bay **(Figure IV-8 and Table IV-6**). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gage site.

The annual freshwater flow record for Halls Creek measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from Halls Creek was 25% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for one hydrologic year beginning September and ending in August (low flow to low flow) was 1,185 m^3/day compared to the long term average flows determined by the USGS modeling effort (1,485 m^3/day).

The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Halls Creek was considered to be negligible given the relatively small flow and associated load. The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured

Table IV-6. Comparison of water flow and nitrogen discharges from Rivers and Streams (freshwater) discharging to estuarine reach of Lewis Bay. The "Stream" data is from the MEP stream gauging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	Halls Crk. Discharge[(a)]	Stewart's Crk. Discharge[(a)]	Snow's Crk. Discharge[(a)]	Hospital Bog Discharge[(a)]	Mill Pond Discharge[(a)]	Chase Brk. Discharge[(a)]	Data Source
Total Days of Record	365[(b)]	365[(b)]	365[(b)]	365[(b)]	365[(b)]	365[(b)]	(1)
Flow Characteristics							
Stream Average Discharge (m3/day) **	1185	13966	5298	1318	15655	3255	(1)
Contributing Area Average Discharge (m3/day)	1485	9712	6339	1126	15699	2321	(2)
Discharge Stream 2003-04 vs. Long-term Discharge	-25%	30%	-20%	15%	-0.28%	29%	
Nitrogen Characteristics							
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.848	1.166	1.14	0.643	0.606	0.45	(1)
Stream Average Total N Concentration (mg N/L)	1.348	2.072	1.899	1.167	1.010	1.035	(1)
Nitrate + Nitrite as Percent of Total N (%)	63%	56%	60%	55%	60%	43%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	1.6	28.93	10.06	1.54	15.81	3.37	(1)
TN Average Contributing UN-attenuated Load (kg/day)	5.02	40.98	21.58	2.72	17.17	5.24	(3)
Attenuation of Nitrogen in Pond/Stream (%)	68%	29%	53%	43%	8%	36%	(4)

(a) Flow and N load to streams discharging to Lewis Bay includes apportionments of Pond contributing areas.
(b) September 1, 2003 to August 31, 2004.
** Flow is an average of annual flow for 2003-2004

(1) MEP gage site data
(2) Calculated from MEP watershed delineations to ponds upgradient of specific gages; the fractional flow path from each sub-watershed which contribute to the flow in the streams to Lewis Bay; and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates.
(4) Calculated based upon the measured TN discharge from the rivers vs. the unattenuated watershed load.

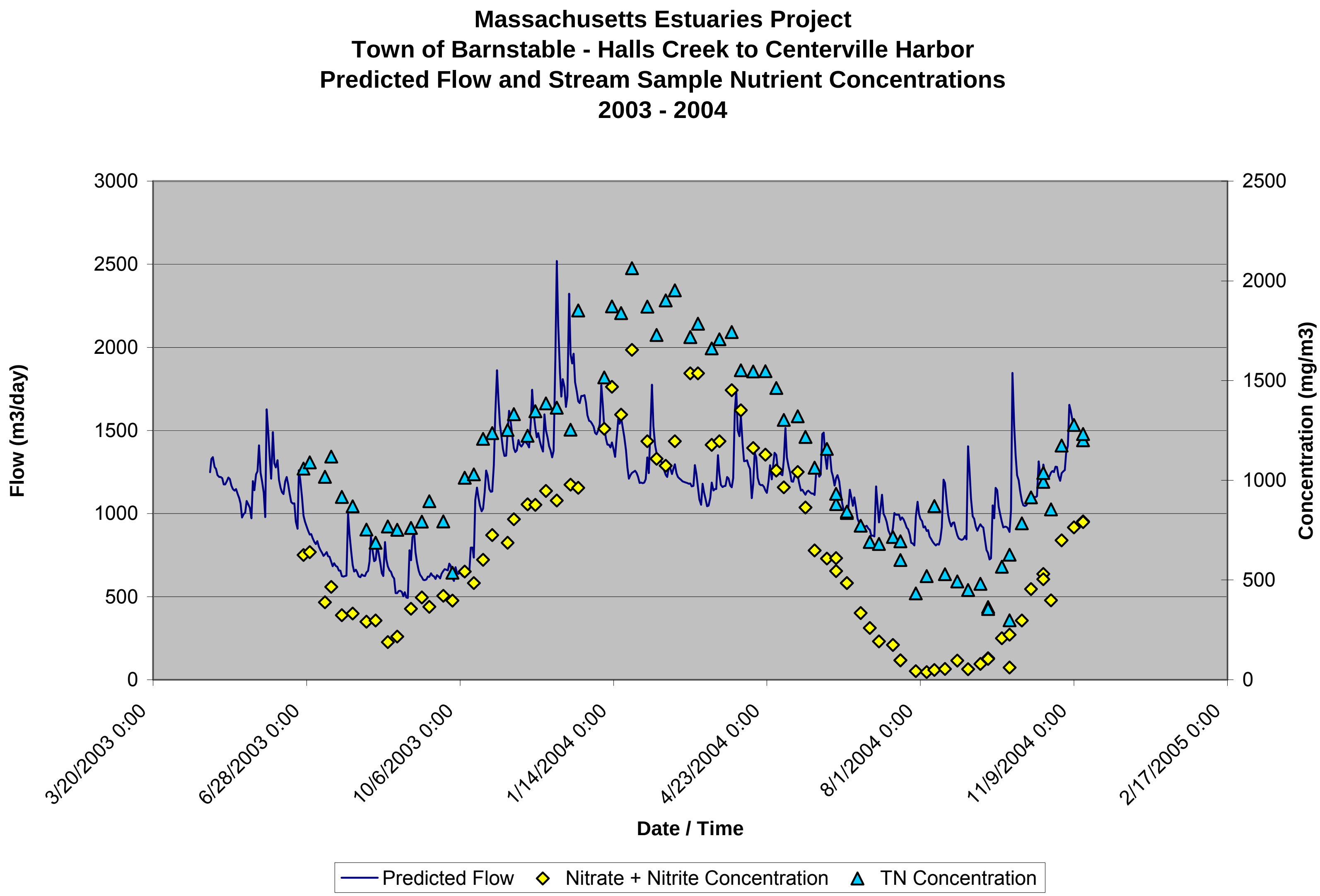


Figure IV-8. Halls Creek discharge (solid blue line), nitrate+nitrite (yellow diamond) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Halls Creek Marsh (Table IV-6).

flow in Halls Creek discharging from Simmons Pond would indicate that the Creek is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Halls Creek outflow were moderate, 1.348 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 1.60 kg/day and a measured total annual TN load of 583 kg/yr. In Halls Creek, nitrate was the predominant form of nitrogen (63%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the pond or stream ecosystems. The high concentration of inorganic nitrogen in the out flowing stream waters also suggests that plant production within the up gradient freshwater ecosystems is not nitrogen limited. In addition, the high nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system either within Simmons Pond or along the freshwater reach of Halls Creek.

From the measured nitrogen load discharged by Halls Creek to the Halls Creek marsh/estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower total nitrogen load (583 kg yr^{-1}) discharged from the freshwater Halls Creek compared to that added by the various land-uses to the associated watershed (1,834 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 68% (i.e. 68% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the hydraulic nature of the network of up gradient ponds capable of attenuating nitrogen . The directly measured nitrogen loads from the river was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Stewart's Creek to the Outer portion of Lewis Bay

Fawcett's Pond and Aunt Bettys Pond located immediately up gradient of the Stewarts Creek gage site are small freshwater ponds and unlike many of the freshwater ponds, these ponds each have stream outflows rather than discharging solely to the aquifer along its down-gradient shore. These stream outflows come together in a wetland area that discharges directly to the outer portion of Lewis Bay through a control structure where the MEP gage was located. These stream outflows to the wetland up gradient of the gage may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetland and must be considered in quantifying the attenuated load of nutrients to outer Lewis Bay. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the wetland above the gage site and the measured annual discharge of nitrogen to outer Lewis Bay relative to the gage, Figure IV-7.

At the Stewarts Creek gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the discharge that carries nitrogen load from the wetland to the outer portion of Lewis Bay. As the Stewarts Creek discharge is tidally influenced the gage was located as far above the saltwater reach such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average low tide salinity was determined to range between 2.5 ppt and 9.8 ppt depending on the season. Based on the salinity, a correction was made to the predicted daily flows obtained at the gage to account for the tidal influence. Considering the weekly salinity data, a boundary salinity obtained from a nearby offshore water quality monitoring station and the ability to correct gage data for salinity, the gage location was deemed acceptable for making freshwater flow measurements at low tide. Calibration of the gage was checked monthly. The gage on Stewarts Creek was installed on April 24, 2003 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued until November 8, 2004 for a total deployment of 18 months. The 12-month uninterrupted record used in this analysis encompasses the summer 2003 and 2004 field season.

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Stewarts Creek site based upon these flow measurements and measured water levels at the gage site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the outer portion of Lewis Bay **(Figure IV-9 and Table IV-6)**. In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gage site.

The annual freshwater flow record for Stewarts Creek measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from Stewarts Creek was 30% above the long-term average modeled flows. Measured flow in Stewarts Creek was obtained for one hydrologic year (September 2003 to August 2004). The average daily flow based on the MEP measured flow data was 13,966 m^3/day compared to the long term average flows determined by the USGS modeling effort (9,712 m^3/day). The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Stewarts Creek flowing to outer portion of Hyannis Harbor is in part be due to a slight tidal influence confounding the freshwater flow record. Due to site constraints, it was necessary to position the stream gage further down gradient in the stream flowing out of the associated marsh. As such, even at low tide, the flow measured in the stream showed a slight salinity as mentioned above. The flow was corrected based on seasonal trends in salinity, however, it is possible that the flow in the stream is a slight over estimate of the freshwater flow discharging to outer Hyannis Harbor. The MEP Technical Team concurred that the over-estimate on flow and therefore load was conservative and used the measured flow and load in the water quality modeling.

Total nitrogen concentrations within the Stewarts Creek outflow were high, 2.072 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 28.93 kg/day and a measured total annual TN load of 10,560 kg/yr. In the Stewarts Creek surface water system, nitrate was the predominant form of nitrogen (56%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the pond, wetland or stream ecosystems. The high concentration of inorganic nitrogen in the out flowing stream waters also suggests that plant production within the up gradient freshwater ecosystems is not nitrogen limited. In addition, the high nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system either within Fawcetts Pond, Aunt Bettys Pond or the wetland up gradient of the Stewarts Creek gage.

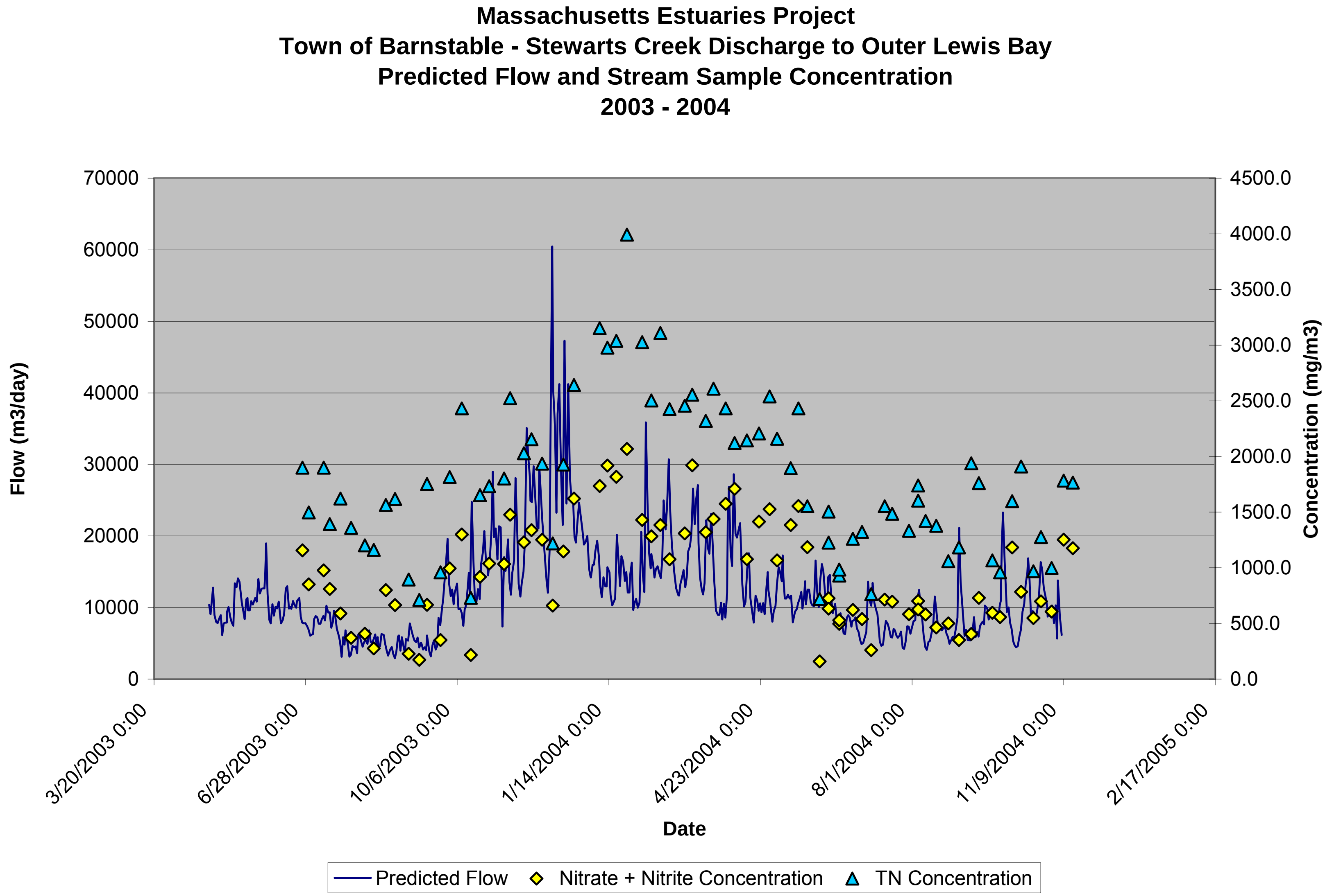


Figure IV-9. Stewart's Creek discharge (solid blue line), nitrate+nitrite (yellow diamond) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to outer Lewis Bay (Table IV-6).

From the measured nitrogen load discharged by Stewarts Creek to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower nitrogen load (10,560 kg yr^{-1}) discharged from the freshwater Stewarts Creek compared to that added by the various land-uses to the associated watershed (14,959 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and wetland prior to discharge to the estuary is 29% (i.e. 29% of nitrogen input to watershed does not reach the estuary). This slightly lower level of attenuation compared to other streams evaluated under the MEP is expected given the hydraulic nature of the up gradient ponds and wetland which are essentially shallow flow through systems. The directly measured nitrogen loads from the creek was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.2.4 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge Snow's Creek to Inner Lewis Bay

Snows Creek is a wetland area with open water that resembles a shallow Pond located immediately up gradient of the gage site. The stream outflow from the wetland up gradient of the gage serves as a location for a direct measurement of the nitrogen attenuation occurring in the wetland. The rate of nitrogen attenuation by biogeochemical processes occurring in the wetland was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the wetland above the gage site and the measured annual discharge of nitrogen to inner Lewis Bay relative to the gage, Figure IV-7.

At the Snows Creek gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the discharge that carries nitrogen load from the wetland to the outer portion of Lewis Bay. As the Snows Creek discharge is tidally influenced the gage was located as far above the saltwater reach such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average low tide salinity was determined to range between 4.5 ppt and 11.3 ppt depending on the season. Based on the salinity, a correction was made to the predicted daily flows obtained at the gage to account for the tidal influence. Considering the weekly salinity data, a boundary salinity obtained from a nearby offshore water quality monitoring station and the ability to correct gage data for salinity, the gage location was deemed acceptable for making freshwater flow measurements at low tide. Calibration of the gage was checked monthly. The gage on Snows Creek was installed on April 24, 2003 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued until November 8, 2004 for a total deployment of 18 months. The 12-month uninterrupted record used in this analysis encompasses the summer 2003 and 2004 field season.

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Snows Creek site based upon these flow measurements and measured water levels at the gage site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the inner portion of Lewis Bay **(Figure IV-10 and Table IV-6)**. In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gage site.

The annual freshwater flow record for Snows Creek measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from Snows Creek was 20% below the long-term average modeled flows. Measured flow in Snows Creek was obtained for one hydrologic year (September 2003 to August 2004). The average daily flow based on the MEP measured flow data was 5,298 m^3/day compared to the long term average flows determined by the USGS modeling effort (6,339 m^3/day). The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Snows Creek are in part due to a slight tidal influence confounding the freshwater flow record. Due to site constraints, it was necessary to position the stream gage further down gradient in the stream flowing out of the associated marsh. As such, even at low tide, the flow measured in the stream showed a slight salinity as mentioned above. The flow was corrected based on seasonal trends in salinity, however, it is possible that the flow in the stream is a slight under estimate of the freshwater flow discharging to outer Hyannis Harbor. The MEP Technical Team concurred that the under-estimate on flow and therefore load was negligible and used the measured flow and load in the water quality modeling.

Total nitrogen concentrations within the Snows Creek outflow were high, 1.899 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 10.06 kg/day and a measured total annual TN load of 3,673 kg/yr. In the Snows Creek surface water system, nitrate was the predominant form of nitrogen (60%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the pond, wetland or stream ecosystems. The high concentration of inorganic nitrogen in the out flowing stream waters also suggests that plant production within the up gradient freshwater ecosystems is not nitrogen limited. In addition, the high nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system within the wetland up gradient of the Snows Creek gage.

From the measured nitrogen load discharged by Snows Creek to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower nitrogen load (3,673 kg yr^{-1}) discharged from the freshwater Snows Creek compared to that added by the various land-uses to the associated watershed (7,875 kg yr^{-1}), the integrated attenuation in passage through the wetland prior to discharge to the estuary is 53% (i.e. 53% of nitrogen input to watershed does not reach the estuary). This moderate level of attenuation compared to other streams evaluated under the MEP is expected given the hydraulic nature of the up gradient wetland which is essentially shallow flow through system and the lack of ponds in the sub-watershed to this gage. The directly measured nitrogen loads from the creek was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

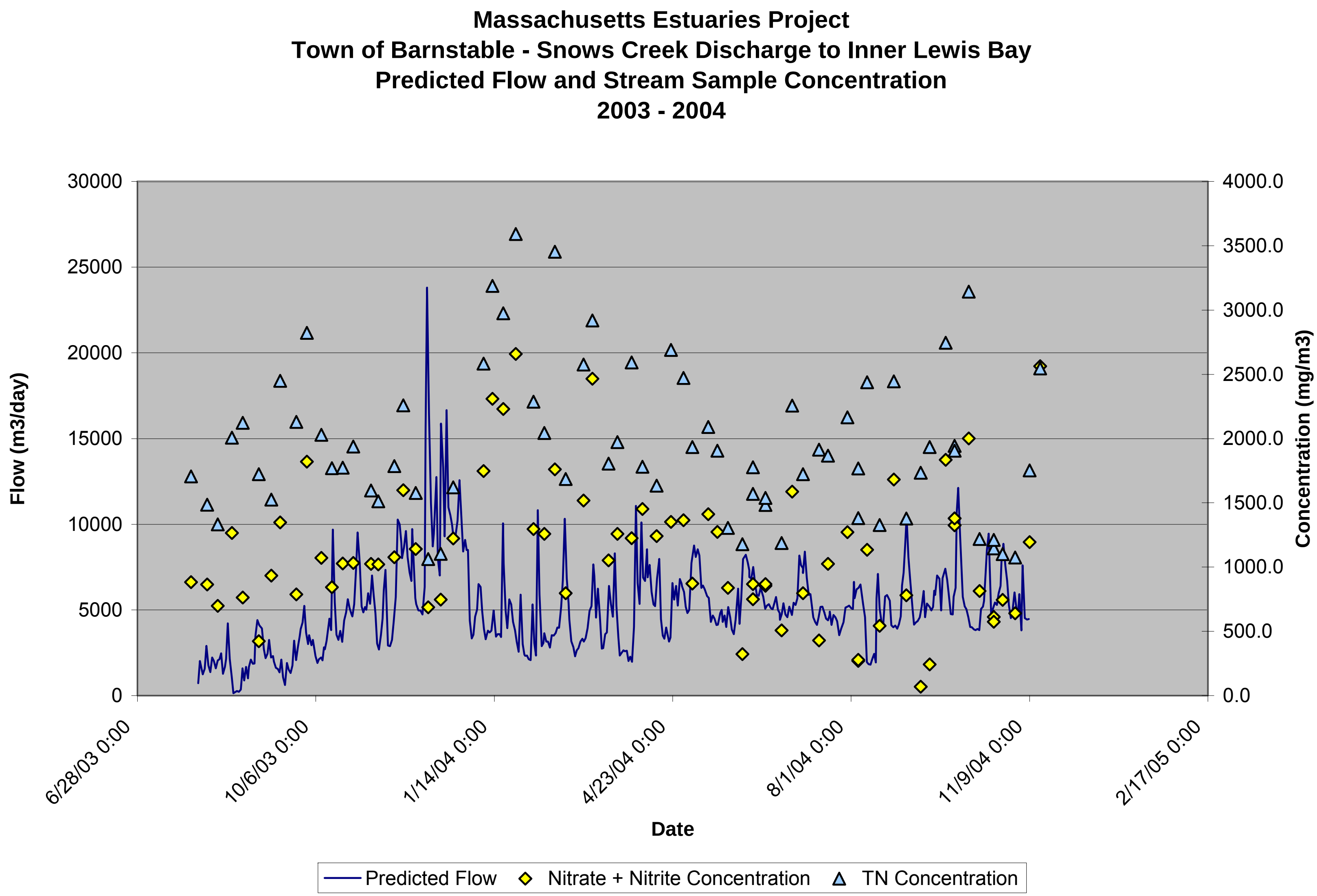


Figure IV-10. Discharge from Snow's Creek (solid blue line), nitrate+nitrite (yellow diamonds) and total nitrogen (blue triangles) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Lewis Bay (Table IV-6).

IV.2.5 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Hospital Bog to Hyannis Inner Harbor

Hospital Bog, located up-gradient of the stream gage site, is a small abandoned cranberry bog that has a stream outflow that provides for a direct measurement of the nitrogen loads and potential attenuation taking place prior to discharge to the inner portion of Hyannis Harbor. In addition, nitrogen attenuation also occurs within the small up-gradient ponds, wetlands and streambed associated with the abandoned bog and the small out flowing stream. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the bog and stream above the gage site and the measured annual discharge of nitrogen to the Lewis Bay system, Figure IV-5.

At the Hospital Bog stream gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the freshwater portion of the stream that carries the flows and associated nitrogen load to the estuarine reach of Lewis Bay via Hyannis Inner Harbor. As the Hospital Bog stream is tidally influenced the gage was located above the saltwater reach such that freshwater flow at low tide could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average low tide salinity was determined to be <0.6 ppt. Therefore, the gage location was deemed acceptable for making freshwater flow measurements. Calibration of the gage was checked monthly. The gage on the stream from Hospital Bog was installed on September 17, 2003 and was set to operate continuously for 16 months such that a complete hydrologic year encompassing both low flow and high flow conditions would be captured in the flow record. Stage data collection continued until April 1, 2005 for a total deployment of 18 months. The 12-month uninterrupted record used in this analysis encompasses the summer 2004 field season. Due to instrument failures, the hydrologic year captured ran from March 2004 to April 2005

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Hospital Bog stream site based upon these flow measurements and measured water levels at the gage site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the estuarine portion of Hyannis Inner Harbor flowing into Lewis Bay (Figure IV-11 and Table IV-6). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gage site.

The annual freshwater flow record for the stream from Hospital Bog measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from the Hospital Bog stream was 15% above the long-term average modeled flows. Measured flow in the Hospital Bog stream was obtained for one hydrologic year (March 2004 to April 2005). The average daily flow based on the MEP measured flow data was 1,318 m^3/day compared to the long term average flows determined by the USGS modeling effort (1,126 m^3/day). The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the Hospital Bog stream was considered to be negligible given the relatively small flow and associated load, as well as the complexity inherent to developing rating curves and predicted flows in marsh/wetland/bog environments. The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the Creek discharging from Hospital Bog would indicate that the Creek is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Hospital Bog stream outflow were moderate to low, 1.167 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 1.54 kg/day and a measured total annual TN load of 561 kg/yr. In the Hospital Bog stream, nitrate was slightly more than half of the total nitrogen load (55%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the up-gradient pond, bog or stream ecosystems. The concentration of inorganic nitrogen in the out-flowing stream waters also suggests that plant production within the up gradient freshwater ecosystems is not nitrogen limited. In addition, the high nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system either within Hospital Bog, small up-gradient ponds or along the freshwater reach of the stream.

From the measured nitrogen load discharged by the Hospital Bog stream discharge to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon the lower nitrogen load (561 kg yr^{-1}) discharged from the freshwater stream compared to that added by the various land-uses to the associated watershed (994 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 43% (i.e. 43% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the hydraulic nature of the up-gradient bog. The directly measured nitrogen loads from the Hospital Bog stream outflow was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.2.6 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Mill Pond to Mill Creek

Mill Pond, located up gradient of the stream gage site is a moderately sized freshwater pond and unlike many of the freshwater ponds, this pond has stream outflow rather than discharging solely to the aquifer along its down-gradient shore. This stream outflow, the Mill Pond stream, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands and streambed associated with the pond and its out-flowing stream. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to Mill Pond and the stream above the gage site and the measured annual discharge of nitrogen to the tidal portion of Mill Creek discharging to Lewis Bay, Figure IV-7.

At the Mill Pond stream gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the freshwater portion of the stream that carries the flows and associated nitrogen load to the estuarine reach of Mill Creek and down-gradient Lewis Bay. As the Mill Pond stream is tidally influenced the gage was located above the saltwater reach such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly

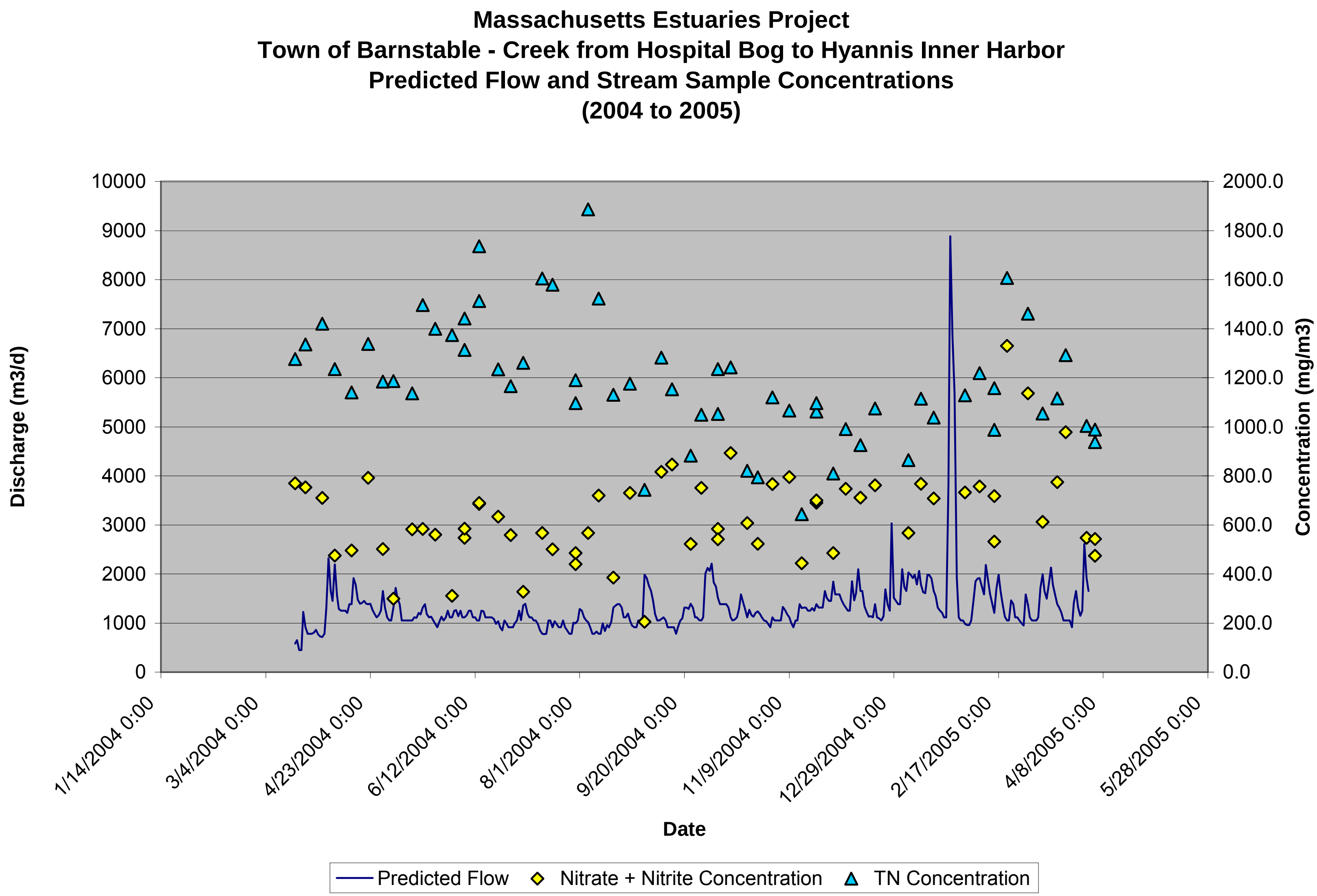


Figure IV-11. Discharge from Hospital Bog (solid blue line), nitrate+nitrite (yellow diamonds) and total nitrogen (blue triangles) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Hyannis Inner Harbor (Table IV-6).

water quality samples collected from the gage site. Average low tide salinity was determined to be <0.2 ppt. Therefore, the gage location was deemed acceptable for making freshwater flow measurements. Calibration of the gage was checked monthly. The gage on the stream from Mill Pond was installed on August 28, 2003 and was set to operate continuously for 16 months such that a complete hydrologic year comprised of both high and low flow periods would be captured in the flow record. Stage data collection continued until April 1, 2005 for a total deployment of 19 months. The 12-month uninterrupted record used in this analysis encompasses the summer 2004 field season.

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Mill Pond stream site based upon these flow measurements and measured water levels at the gage site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the estuarine portion of Mill Creek flowing into Lewis Bay (Figure IV-12 and Table IV-6). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gage site.

The annual freshwater flow record for the stream from Mill Pond to Mill Creek measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from the Mill Pond stream compared favorably with the long-term average modeled flows. Measured flow in the Mill Pond stream was obtained for one hydrologic year (September 2003 to September 2004). The average daily flow based on the MEP measured flow data was 15,655 m^3/day compared to the long term average flows determined by the USGS modeling effort (15,699 m^3/day). The lack of difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the Mill Pond stream would indicate that the stream is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Mill Pond stream outflow were low to moderate, 1.010 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 15.81 kg/day and a measured total annual TN load of 5,772 kg/yr. In the Mill Pond stream, nitrate was the predominant form of nitrogen (60%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the pond or stream ecosystems. The high concentration of inorganic nitrogen in the out flowing stream waters also suggests that plant production within the up-gradient freshwater ecosystems is not nitrogen limited. In addition, the high nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system either within Lake Elizabeth or along the freshwater reach of the stream.

From the measured nitrogen load discharged by the Mill Pond stream discharge to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon the lower nitrogen load (5,772 kg yr^{-1}) discharged from the freshwater stream compared to that added by the various land-uses to the associated watershed (6,266 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 8% (i.e. 8% of nitrogen input to

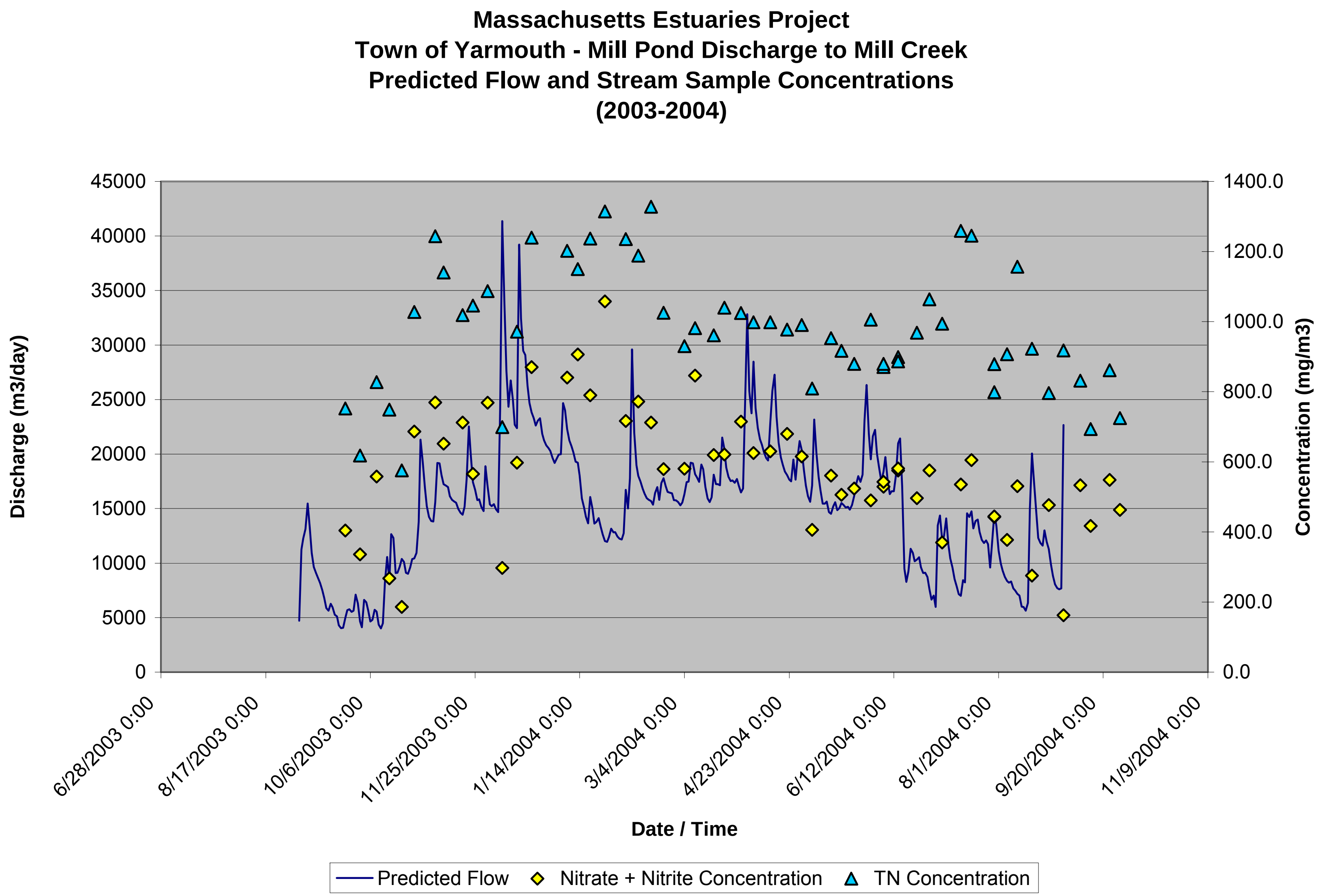


Figure IV-12. Discharge from Mill Pond (solid blue line), nitrate+nitrite (yellow diamond) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Mill Creek (Table IV-6).

watershed does not reach the estuary). This low level of attenuation compared to other streams evaluated under the MEP is expected given the hydraulic nature of the up-gradient pond which is essentially a shallow flow through pond system with small residence time. The directly measured nitrogen loads from the stream was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.2.7 Surface water Discharge and Attenuation of Watershed Nitrogen: Chase Brook Discharge to Mill Creek

Horse Pond, Jabinettes Pond and the cranberry bog up-gradient of the stream gage site is a network of small freshwater ponds and bogs and unlike some aquatic systems on Cape Cod, has stream outflow rather than discharging solely to the aquifer along down-gradient shorelines. The stream outflow, Chase Brook, may serve to decrease the attenuation of nitrogen in up gradient ponds, however, it does provide for a direct measurement of the nitrogen attenuation occurring within the freshwater aquatic system as a whole. In addition, nitrogen attenuation also occurs within the wetlands and streambed associated with the ponds, bogs and the out flowing stream (Chase Brook). The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the ponds, bogs and stream above the gage site and the measured annual discharge of nitrogen to the tidal portion of Mill Creek discharging to Lewis Bay, Figure IV-7.

At the Chase Brook stream gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the freshwater portion of the stream that carries the flows and associated nitrogen load to the estuarine reach of Mill Creek and down gradient Lewis Bay. As Chase Brook is tidally influenced the gage was located above the saltwater reach such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average low tide salinity was determined to be <0.4 ppt. Therefore, the gage location was deemed acceptable for making freshwater flow measurements. Calibration of the gage was checked monthly. The gage on Chase Brook flowing from the active up-gradient cranberry bog was installed on April 29, 2004 and was set to operate continuously for 16 months such that two summer seasons (2004 and 2005) would be captured in the flow record. Stage data collection continued until November 8, 2005 for a total deployment of 19 months. The 12-month uninterrupted record used in this analysis encompasses the summer 2005 field seasons.

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Chase Brook gage site based upon these flow measurements and measured water levels at the gage site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the estuarine portion of Mill Creek and Down gradient Lewis Bay (Figure IV-13 and Table IV-6). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gage site.

The annual freshwater flow record for Chase Brook measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from Chase Brook was 29% above the long-term average modeled flows. Measured flow in Chase Brook was obtained for one hydrologic year

(September 2004 to August 2005). The average daily flow based on the MEP measured flow data was 3,255 m^3/day compared to the long term average flows determined by the USGS modeling effort (2,321 m^3/day). The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Chase Creek flowing to the estuarine reach of Mill Creek is in part be due to a slight tidal influence confounding the freshwater flow record. Due to site constraints, it was necessary to position the stream gage further down gradient in the stream flowing under Route 28. As such, for small portions of the day head differentials vary thereby potentially limiting freshwater discharge for a small fraction of a 24 hr period. The flow was corrected to account for tidal influence based on the 2 to 4 hours out of every day where the highest part of the tide would be limiting flow in the creek. Even so, it is possible that the flow in the stream is a slight over estimate of the freshwater flow discharging to Mill Creek. The MEP Technical Team concurred that the over-estimate on flow and therefore load was conservative and used the measured flow and load in the water quality modeling.

Total nitrogen concentrations within the Chase Brook outflow were low to moderate, 1.035 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 3.37 kg/day and a measured total annual TN load of 1,230 kg/yr. In Chase Brook, nitrate was nearly half the total nitrogen load (43%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the pond, bog or stream ecosystems. The concentration of inorganic nitrogen in the out flowing stream water also suggests that plant production within the up gradient freshwater ecosystems is not nitrogen limited. In addition, the moderate nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system either within the bog, Horse Pond, Jabinettes Pond or along the freshwater reach of the stream.

From the measured nitrogen load discharged by Chase Brook to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon the lower nitrogen load (1,230 kg yr^{-1}) discharged from the freshwater stream compared to that added by the various land-uses to the associated watershed (1,911 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 36% (i.e. 36% of nitrogen input to watershed does not reach the estuary). This relatively low level of attenuation compared to other streams evaluated under the MEP is expected given the hydraulic nature of the up-gradient ponds and bog which are essentially flow through aquatic systems with relatively short residence times. The directly measured nitrogen loads from Chase Brook was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the benthic nutrient flux Surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters throughout the Lewis Bay 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.

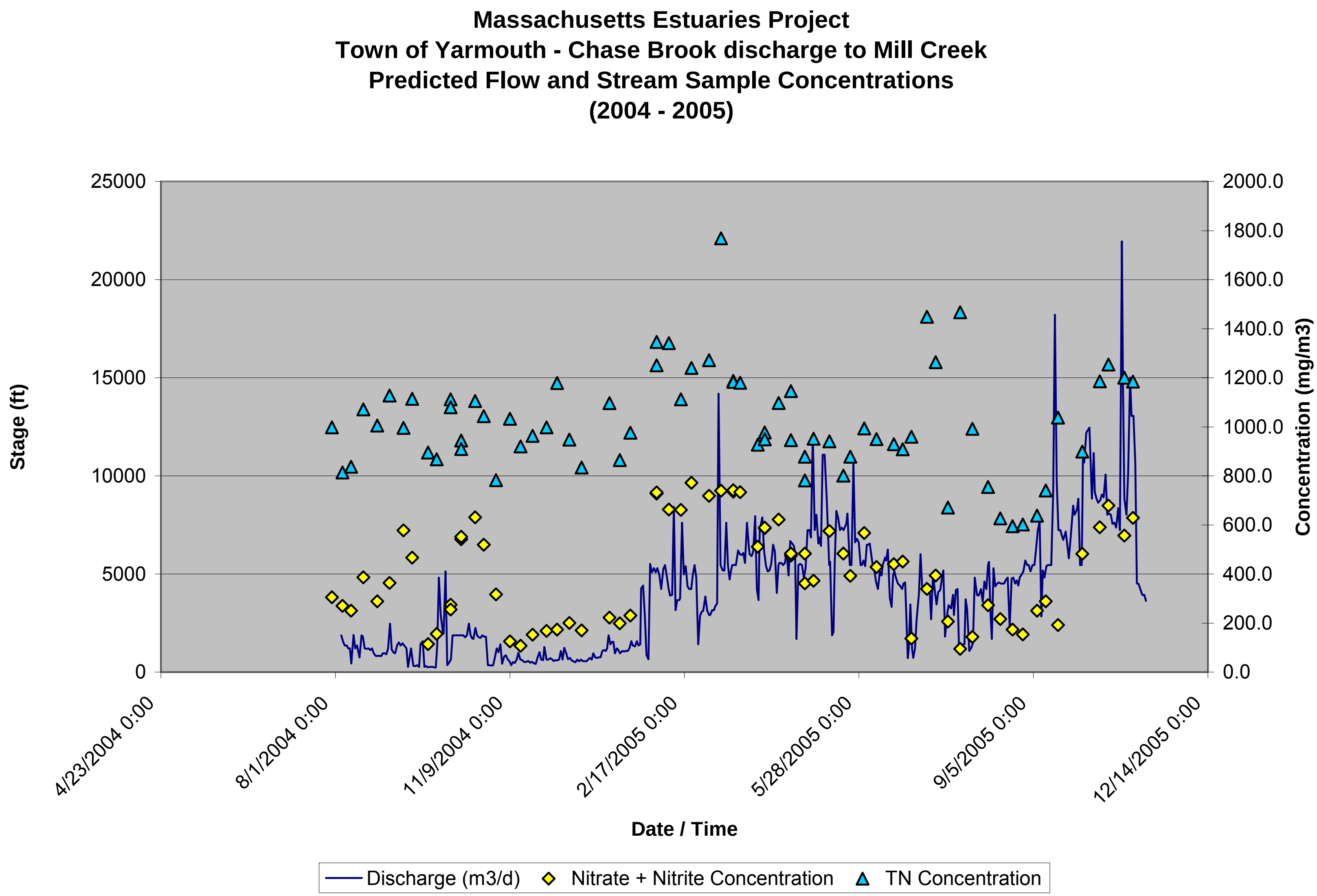


Figure IV-13. Discharge from Chase Brook (solid blue line), nitrate+nitrite (yellow diamond) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Mill Creek (Table IV-6).

Table IV-7. Summary of annual volumetric discharge and nitrogen load from the Rivers and Streams (freshwater) discharging to the Lewis Bay system based upon the data presented in Figures IV-6 through IV-9 and Table IV-6.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Halls Creek (MEP)	**September 1, 2003 to August 31, 2004**	**432597**	**367**	**583**
Halls Creek (CCC)	Based on Watershed Area and Recharge	541985	--	--
Stewart's Creek (Freshwater) MEP	**September 1, 2003 to August 31, 2004**	**5097413**	**5943**	**10560**
Stewart's Creek (Freshwater) CCC	Based on Watershed Area and Recharge	3544836	--	--
Snow's Creek (Freshwater) MEP	**September 1, 2003 to August 31, 2004**	**1933944**	**2206**	**3673**
Snow's Creek (Freshwater) CCC	Based on Watershed Area and Recharge	2313712	--	--
Creek to Hyannis Inner Harbor (MEP) aka. Hospital Bog	**September 1, 2004 to August 31, 2005**	**480912**	**309**	**561**
Creek to Hyannis Inner Harbor (CCC) aka. Hospital Bog	Based on Watershed Area and Recharge	410961	--	--
Mill Pond Stream (MEP)	**September 24, 2003 to September 23, 2004**	**5714176**	**3465**	**5772**
Mill Pond Stream (CCC)	Based on Watershed Area and Recharge	5730166	--	--
Chase Brook (MEP)	**September 1, 2004 to August 31, 2005**	**1188175**	**535**	**1230**
Chase Brook (CCC)	Based on Watershed Area and Recharge	847273	--	--

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

As stated in above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the complex Lewis Bay Embayment System predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like 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 bioavailable nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh). The Mill Creek sub-embayment of the Lewis Bay System is predominantly such a salt marsh basin, as is the adjacent estuary of Halls Creek. Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, such as found within much of the bordering region to the Lewis Bay main basin. In contrast, regions of high deposition like Hyannis Inner Harbor, which is essentially a dredged boat basin and channel, typically support anoxic sediments with elevated rates of nitrogen release during summer months. The consequence of this deposition is that the basin sediments are unconsolidated, organic rich and sulfidic nature (MEP field observations).

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading to the Lewis Bay 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-watercolumn nitrogen exchange

For the Lewis Bay Embayment System, and Halls Creek in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected from 28 sites, 24 within Lewis Bay and its tributary sub-embayments and 4 in the nearby Halls Creek Salt Marsh (Figure IV-14) in July-August 2004. 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-14 per incubation are as follows:

Lewis Bay Embayment System Benthic Nutrient Regeneration Cores

- Lewis Bay East-1 — 1 core — (Basin)
- Lewis Bay East-2 — 1 core — (Basin)
- Lewis Bay East-3 — 1 core — (Basin)
- Lewis Bay East-4 — 1 core — (Basin)
- Lewis Bay Main-5 — 1 core — (Basin)
- Lewis Bay Main-6 — 1 core — (Basin)
- Lewis Bay Main-12 — 1 core — (Basin)
- Lewis Bay Main-13 — 1 core — (Basin)
- Lewis Bay Main-14 — 1 core — (Basin)
- Lewis Bay Main-15 — 1 core — (Basin)
- Lewis Bay Main-16 — 1 core — (Basin)
- Lewis Bay West-17 — 1 core — (Basin)
- Lewis Bay West-18 — 1 core — (Basin)
- Lewis Bay West-19 — 1 core — (Basin)
- Mill Creek - 9 — 1 core — (Marsh Basin)
- Mill Creek -10 — 1 core — (Marsh Basin)
- Mill Creek -11 — 1 core — (Marsh Basin)
- Hyannis Hbr Outer-20 — 1 core — (Basin)
- Hyannis Hbr Inner-21 — 1 core — (Basin)
- Hyannis Hbr Inner-22 — 1 core — (Basin)
- Hyannis Hbr Marina-23 — 1 core — (Basin)
- Uncle Roberts Cove-7 — 1 core — (Basin)
- Uncle Roberts Cove-8 — 1 core — (Basin)

Halls Creek Salt Marsh Benthic Nutrient Regeneration Cores

- Halls Creek -7 — 1 core — (Marsh Creek)
- Halls Creek -8 — 1 core — (Marsh Creek)
- Halls Creek Lower -5 — 1 core — (Marsh Creek)
- Halls Creek -6 — 1 core — (Marsh Creek)

Figure IV-14. Lewis Bay and Halls Creek embayment system sediment sampling sites (green symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above.

Sampling was distributed throughout the primary embayment sub-basins of this system: Mill Creek, Hyannis Inner Harbor, Uncle Roberts Cove, Lewis Bay (and adjacent Halls Creek Salt Marsh) and the results for each site combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

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

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

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

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

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

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

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

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-15).

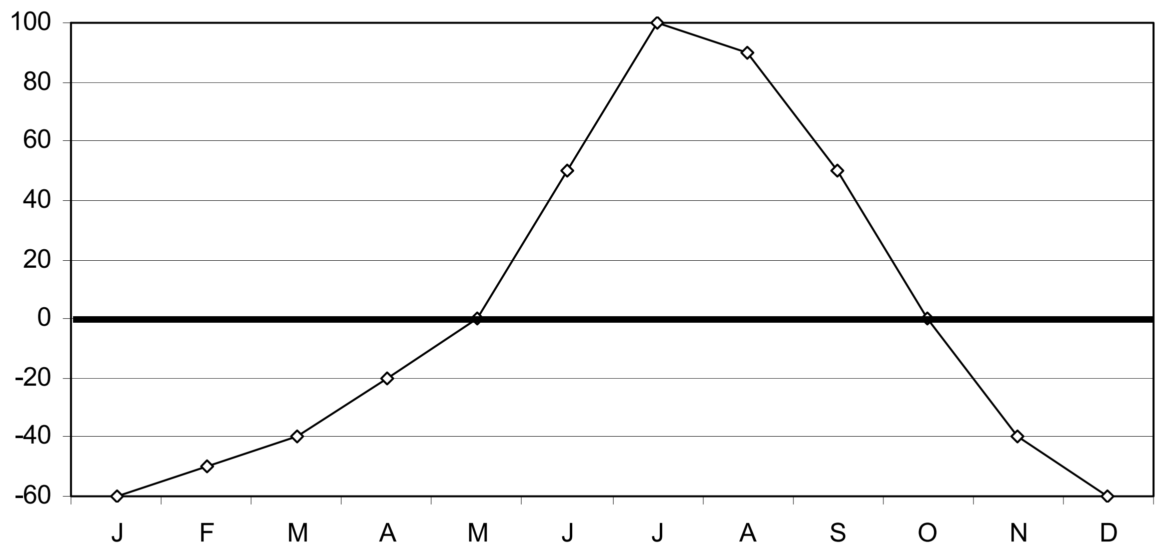


Figure IV-15 Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

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

Sediment sampling was conducted throughout the primary embayment sub-basins of this system: Mill Creek, Hyannis Inner Harbor, Uncle Roberts Cove, Lewis Bay (and adjacent Halls Creek Salt Marsh) in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. 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 and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

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

Net nitrogen release or uptake from the sediments within the Lewis Bay Embayment System (and adjacent Halls Creek) were comparable to other similar embayments with similar configuration and flushing rates in southeastern. Massachusetts. In addition, the pattern of sediment N release was also similar to other systems, with the salt marsh basins and creeks showing net nitrogen uptake, the embayment depositional basins showing net nitrogen release and the marginal main basin sediments, which were oxidized, showing net nitrogen uptake. Sediment nitrogen release in the central basin of Lewis Bay and the smaller enclosed basins of Uncle Roberts Cove and Hyannis Harbor were low to moderate, ranging from 6.9 mg N m^{-2} d^{-1}

in the main basin to 1.73 - 63.8 mg N m^{-2} d^{-1} in the enclosed basins. These rates are consistent with the depositional nature of these basins and the more nutrient enriched waters of the smaller tributary basins. Only the highly organic anoxic sediments of the dredged basin in the marina region of inner Hyannis Harbor showed high rates of nitrogen release. This data is consistent with the clearly high deposition in this region and the sulfidic nature of the sediments. The finding of higher rates of summer nitrogen release in smaller semi enclosed basins is common on Cape Cod. For example Rock Harbor, Orleans, showed moderate/high rates of nitrogen release, 80.8 mg N m^{-2} d^{-1}, similar to the Pleasant Bay sub-basins of Meetinghouse Pond, Areys Pond, Paw Wah Pond, 79.5, 107.3, 120.7 mg N m^{-2} d^{-1}, respectively, whereas the main basins of Pleasant Bay were similar to the main basin of Lewis Bay, -1.1 to 16.0 mg N m^{-2} d^{-1}. In addition, the salt marsh rates of uptake were also similar to other nearby marsh systems. For example, net nitrogen uptake Mill Creek (-14.3 mg N m^{-1} d^{-1}) was similar to that observed for the salt marsh areas in the Centerville River System (-4.5 to -13.2 mg N m^{-1} d^{-1}) and lower Halls Creek, -11.1 mg N m^{-1} d^{-1} (MEP Centerville River Final Nutrient Technical Report 2006) a general pattern seen in a number of estuaries of similar structure within the MEP region (MEP Cockle Cove Technical Memorandum-Howes et al. 2006).

Net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the Lewis Bay Embayment System (Chapter VI) are presented in Table IV-8. There was a clear spatial pattern of sediment nitrogen flux, with net uptake of nitrogen by the salt marsh basin and marginal Lewis Bay basin sediments and net release by the sediments of the depositional regions of the embayment system. The sediments within the Lewis Bay Embayment System showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to this system and its relatively high flushing rate.

Table IV-8. Rates of net nitrogen return from sediments to the overlying waters of the Lewis Bay Estuarine System and the adjacent Halls Creek Salt Marsh. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July -August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			i.d. *
	Mean	S.E.	# sites	
Lewis Bay Embayment System				
Mill Creek Salt Marsh Basin	-14.3	7.6	3	LWB 9,10,11
Hyannis Harbor - Outer	63.8	39.6	2	LWB 20, 21
Hyannis Harbor - Inner	20.4	16.2	2	LWB 22,23
Hyannis Harbor - Marina	143.5	3.6	1	LWB 24
Uncle Roberts Cove	17.3	13.4	2	LWB 7,8
Lewis Bay East Basin	-11.6	12.7	4	LWB 1,2,3,4
Lewis Bay Main Basin	6.9	18.7	7	LWB 5,6,12-16
Lewis Bay West Basin	-32.0	8.8	3	LWB 17-19
Halls Creek Salt Marsh				
Halls Creek Upper	31.6	2.3	2	HC 7,8
Halls Creek Lower	-11.1	7.0	2	HC 5,6

* Station numbers refer to Figure IV-14.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

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

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

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

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

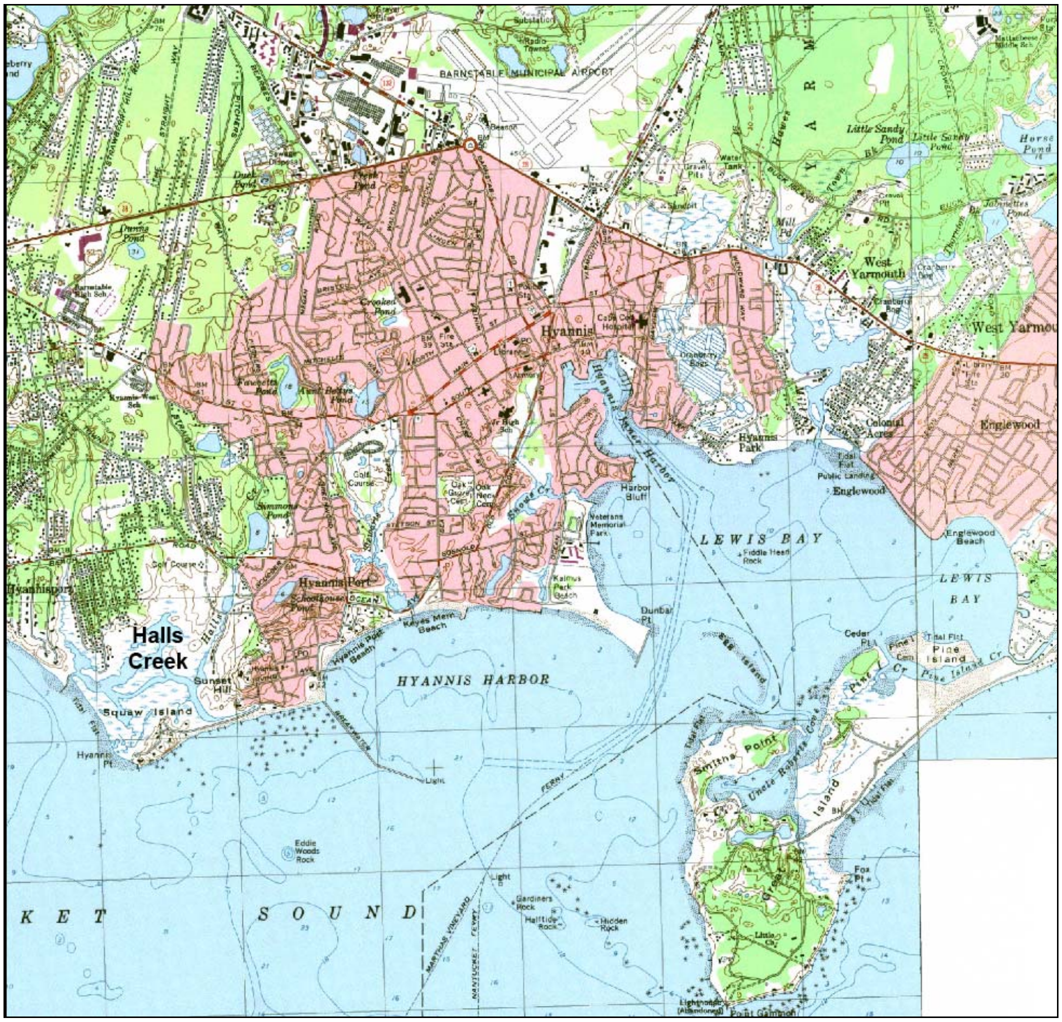


Figure V-1. Map of the Lewis Bay and Halls Creek estuary systems (from United States Geological Survey topographic maps).

To understand the dynamics of Lewis Bay and Halls Creek, a hydrodynamic study was performed for both separate systems. Lewis Bay is surrounded by the towns of Barnstable and Yarmouth along the south coast of Cape Cod, Massachusetts, while Halls Creek lies within the municipal boundary of Barnstable. A site map showing the study area is shown in Figure V-1.

The Lewis Bay system includes Hyannis Harbor which is the entrance to the system from Nantucket Sound. There is minimal restriction from Nantucket Sound into Hyannis Harbor, except for a rubble mound jetty located along the west edge of the harbor. Along the north side of the Hyannis Harbor is Stewarts Creek, a shallow sub-embayment connected through a 36-inch culvert. Lewis Bay opens out from Hyannis Harbor and has a number of smaller embayments along its boundary. Snows Creek to the west, Hyannis Inner Harbor and Mill Creek to the north, Sweetheart and Pine Island Creeks to the east, and to the south is Uncle Roberts Cove. The approximate tidal range within the system is 5.5 feet, with Nantucket Sound tidal variations providing the hydraulic forcing that drives water movement throughout the system.

Lewis Bay and the adjoining embayments are shallow tidal estuaries, with a mean water depth of only 3.0 feet. Salt marsh areas are contained on the margins of the smaller embayments off of Lewis Bay. The smaller embayments contain approximately 110 acres of marsh, which accounts for 5 percent of the total estuary surface area.

The entire Halls Creek system has a surface coverage of 140 acres, which includes 82 acres of marsh plain. Like Lewis Bay, circulation in Halls Creek is dominated by tidal exchange with Nantucket Sound, through an inlet with one jetty. This system also has a shallow mean depth (approximately -0.4 feet NGVD)

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

Circulation in Lewis Bay and Halls Creek systems were simulated using the RMA-2 numerical hydrodynamic model. To calibrate the model, field measurements of water elevations and bathymetry were required. For Lewsi Bay, tide data were acquired within Nantucket Sound at a gage station installed offshore of Hyannis Harbor, and also at nine stations located within the estuary (Figure V-2). For Halls Creek, tide data were collected at a station offshore in the system, in Nantucket Sound, and also at a station inside the Creek Inlet (Figure V-3). All temperature-depth recorders (TDRs or tide gages) were installed for at least a 30-day period to measure tidal variations through one lunar month. In this manner, attenuation of the tidal signal as it propagates through the various sub-embayments was evaluated accurately.

V.2 FIELD DATA COLLECTION AND ANALYSIS

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

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

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

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

To complete the field data collection effort for this study, and to provide model verification data, a survey of velocities was completed at the entrance to Lewis Bay, Inner Hyannis Harbor, and Mill Creek. The survey was performed to determine flow rates at the inlets at discreet times during the course of a full tide cycle.

V.2.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic models of the Lewis Bay and Halls Creek systems were assembled from a hydrographic survey performed specifically for this study and historical NOS survey data, where availible. The NOS data were used for areas in Nantucket Sound that were not covered by the more recent survey.

The hydrographic surveys of both systems were conducted in July of 2004. The survey of Lewis Bay was designed to collect coverage of the shallow water areas between Hyannis Harbor and Lewis Bay, Mill Creek, Pine Island Creek, Uncle Roberts Cove, and Snows Creek. Survey transects were densest in the vicinity of the inlets, were the greatest variability in bottom bathymetry was expected. Bathymetry data in the inlets of each separate system are important from the standpoint that it has the most influence on tidal circulation in and out of the estuary.

Each survey utilized a small boat with an installed precision fathometer (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide position measurements accurate to approximately 1-3 feet. In the shallow channels of each system, soundings were collected manually using a graduated staff. For both the fathometer and manual portions of the survey, positioning data were collected using a differential GPS.

All bathymetry data were tide corrected, and referenced to the North Geodetic Vertical Datum of 1929 (NGVD 29), using survey benchmarks located in the project area. Once rectified, the finished processed data were archived as ‘xyz’ files containing x-y horizontal position (in Massachusetts State Plan 1983 coordinates) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The final processed bathymetric data from the survey are presented in Figure V-3 for Lewis Bay and V-4 for Halls Creek.

Results from the survey show that the deepest point (-9.9 ft NGVD) within Halls Creek is located in the inlet channel. The remaining channels of the Creek are generally shallow, between -2.0 and 0.0 ft NGVD. Apart from the marsh plain, the shallowest area of the Creek is located at the small flood shoal near the inlet, were the minimum depth is +1.5 NGVD.

In Lewis Bay, the greatest depths (approximately -15 ft NGVD) are found within the main navigation channel. Beyond the channel, the greatest natural depth is approximately -13 ft NGVD. Outside Lewis Bay, in Hyannis Harbor the greatest water depths within the breakwater are more than 20 ft.

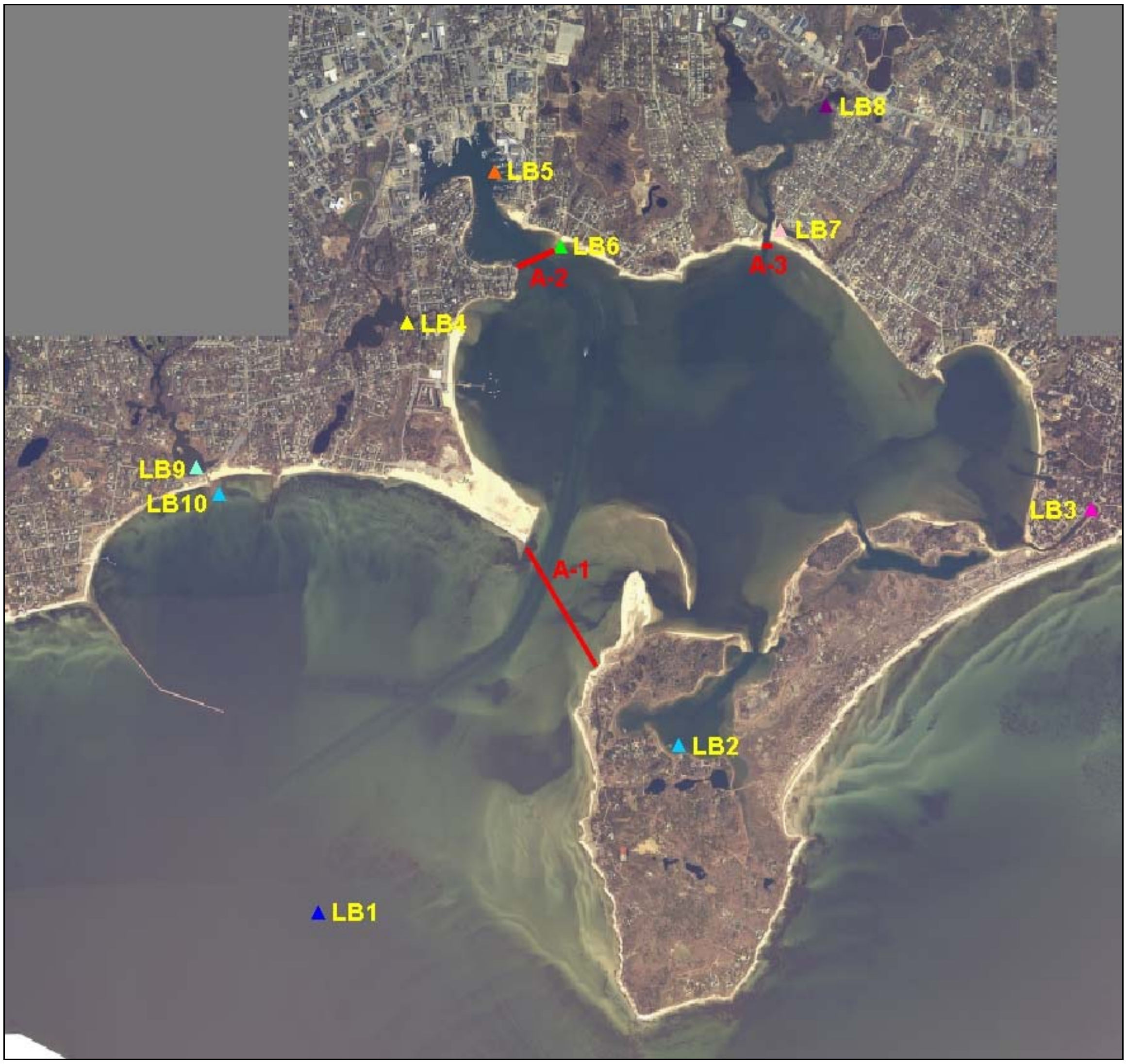


Figure V-2. Map of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. Eight (8) gauges were deployed for the 55-day period between May 27, and July 21, 2004. The colored triangles represents the approximate locations of the tide gauges: (LB1) represents the gage in Nantucket Sound (Offshore), (LB2) inside the Uncle Roberts Cove, (LB3) in Sweetheart Creek, (LB4) in Snows Creek, (LB5) Hyannis Inner Harbor at Hyannis Marine, (LB6) at Bayview Beach, (LB7) lower end of Mill Creek, and (LB8) upper reach of Mill Creek. Two (2) gauges (LB9 and LB10) were deployed at Stewarts Creek for a 16-day period between May 12, and May 31, 2007.

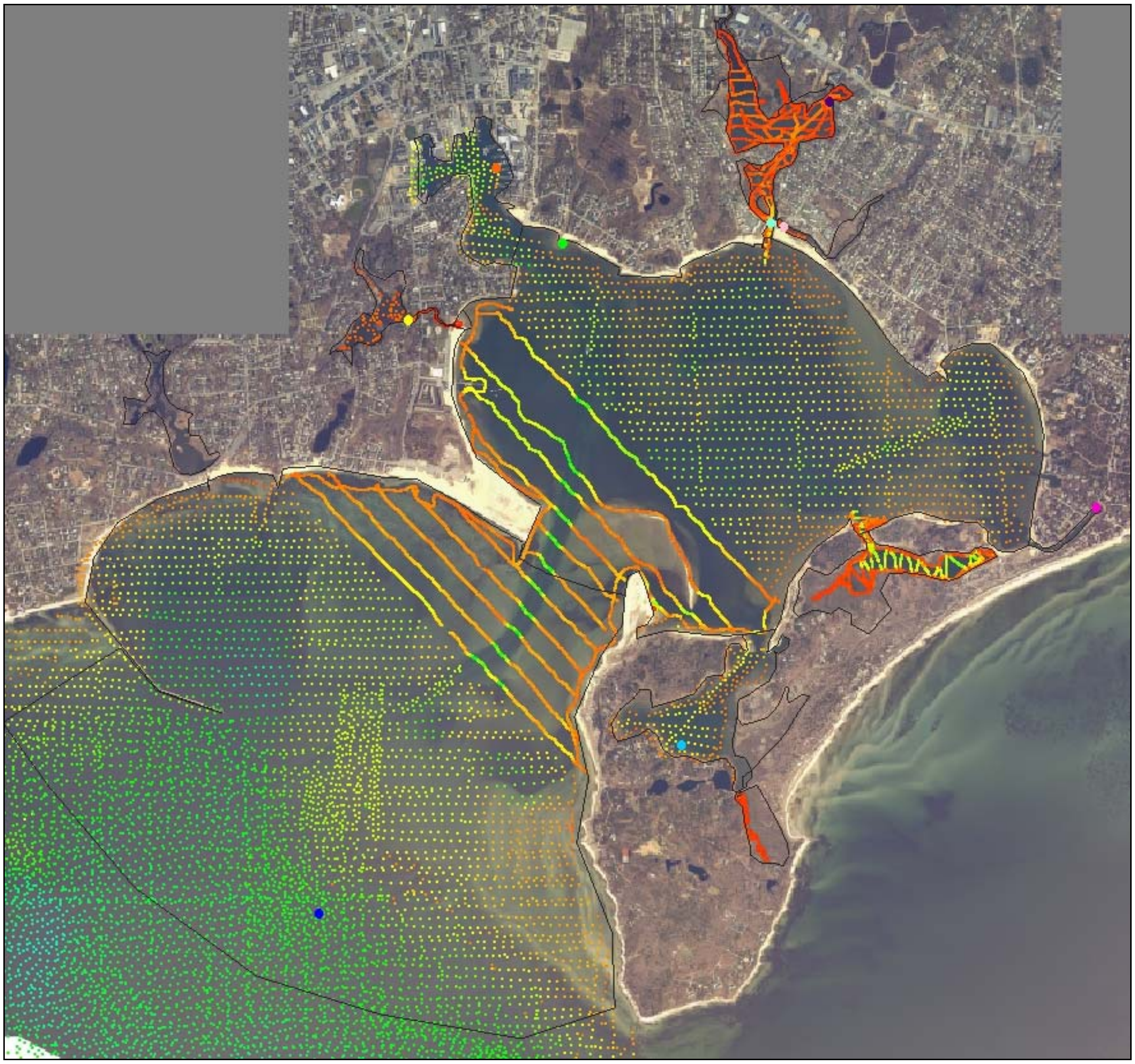


Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

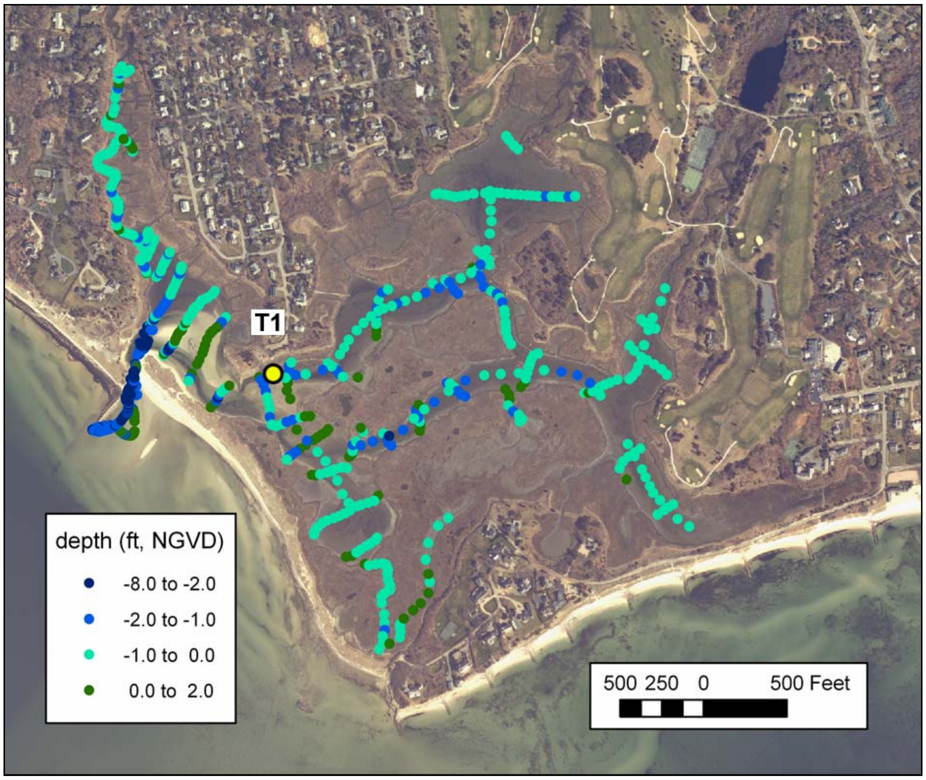


Figure V-4. Transects from the bathymetry survey of the Halls Creek. The yellow marker shows the location of the tide data recorder deployed inside the Creek for this study.

V.2.2 Tide Data Collection and Analysis

V.2.2.1 Lewis Bay

Variations in water surface elevation were measured at a station in at nine locations in the Lewis Bay, and at a single station in Nantucket Sound. Stations within the Lewis Bay were located inside the Uncle Roberts Cove (LB2), in Sweetheart Creek (LB3), in Snows Creek (LB4), at Hyannis Marine with Hyannis Inner Harbor (LB5), at Bayview Beach in Lewis Bay (LB6), at the lower end of Mill Creek (LB7), and (LB8) upper reach of Mill Creek. These eight gauges were deployed for the 55-day period between May 27, and July 21, 2004. The gauging stations for Stewarts Creek were deployed over a later time period between May 12, and May 31, 2007. Station LB9 is within Stewarts Creek, and Station LB10 is within the Lewis Bay located at the end of the jetty. The duration of the TDR deployment allowed time to conduct the ADCP and bathymetric surveys, as well as sufficient data to perform a thorough analysis of the tides in the system.

The tide records from Lewis Bay were corrected for atmospheric pressure variations and then rectified to the NGVD 29 vertical datum. Atmospheric pressure data, available in one-hour intervals from the NDBC Nantucket Sound C-MAN platform, were used to pressure correct the raw tide data. Final processed tide data from stations used for this study are presented in Figure V-5, for the complete 55-day period of the TDR deployment.

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

The loss of amplitude together with increasing phase delay with increasing distance from the inlet is described as tidal attenuation. Tide attenuation can be a useful indicator of flushing efficiency in an estuary. Attenuation of the tidal signal is caused by the geomorphology of the nearshore region, where channel restrictions (e.g., bridge abutments, roadway culverts, inlets) and also the depth of an estuary are the primary factors which influence tidal damping in estuaries. For Lewis Bay, a visual comparison in Figure V-6 between tide elevations at seven stations along the system demonstrates how little change there is between the tide range and timing from Nantucket Sound to the farthest inland reaches of the Lewis Bay, Uncle Roberts Cove, Mill Creek, and Sweetheart Creek. The only significant amplitude reduction being caused by the culvert under Ocean Street connecting Snows Creek to Lewis Bay. This provides an initial indication that flushing conditions in the prior mentioned are ideal, with minimal loss of tidal energy along the length of the system except into Snows Creek.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the tide records. These datums are presented in Table V-1. The Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW. The tides in Nantucket Sound are semi-diurnal, meaning that there are typically two tide cycles in a day. There is usually a small variation in the level of the two daily tides. This variation can be seen in the differences between the MHHW and MHW, as well as the MLLW and MLW levels. The computed datums for Lewis Bay and Nantucket Sound compare well to similar datums computed for the Centerville River using a 29-day record from 2004 (MTL 0.6 ft, MHW 1.9 ft, MLW -0.7 ft NGVD).

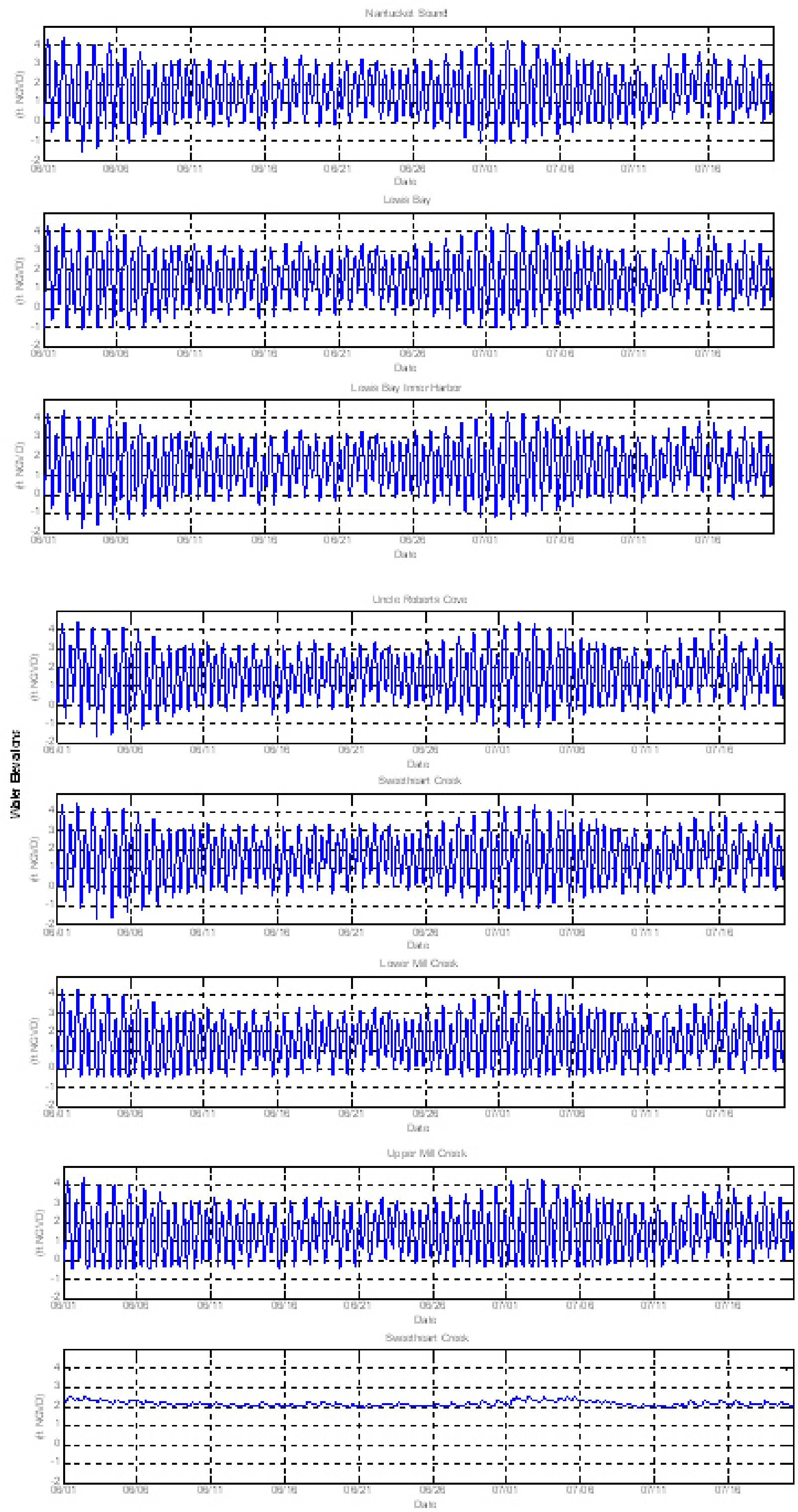


Figure V-5 Water elevation variations as measured at the seven locations within the Lewis Bay system, between June 1 and July 21, 2004.

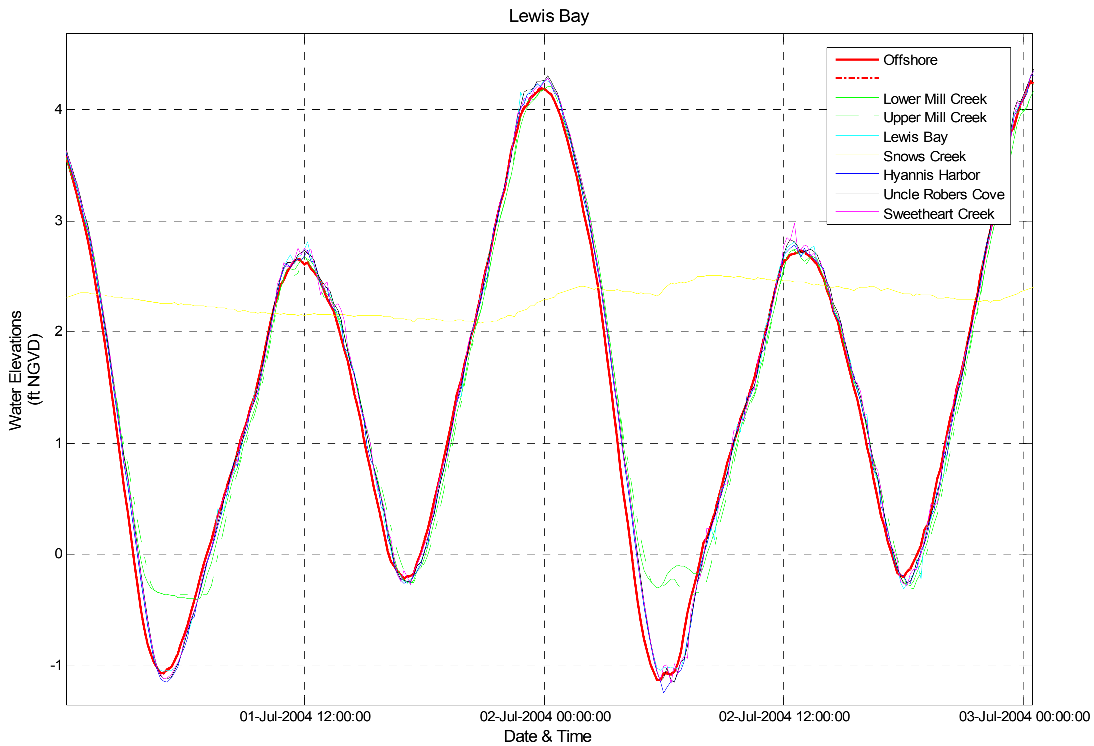


Figure V-6 Plot showing two tide cycles tides at seven stations in the Lewis Bay system plotted together. Demonstrated in this plot is the amplitude reduction in Snows Creek caused by the propagation of the tide through the culvert under Ocean Street.

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

Table V-1. Tide datums computed from records collected in the Lewis Bay system June 1 - July 21, 2004. Datum elevations are given in feet relative to NGVD 27.

Tide Datum	Nantucket Sound	Lewis Bay	Inner Harbor	Uncle Roberts Cove	Sweetheart Creek	Upper Mill Creek	Lower Mill Creek	Snows Creek
Maximum Tide	4.36	4.46	4.50	4.48	4.49	4.46	4.46	3.06
MHHW	3.49	3.56	3.63	3.57	3.60	6.59	3.56	2.79
MHW	3.05	3.09	3.16	3.10	3.10	3.09	3.09	2.73
MTL	1.52	1.51	1.57	1.51	1.51	1.59	1.51	2.67
MLW	-0.01	-0.7	-0.07	-0.07	-0.08	0.09	-0.07	2.61
MLLW	-0.36	-0.41	-0.39	-0.44	-0.47	-0.14	-0.41	2.57
Minimum Tide	-1.54	-1.08	-1.65	-1.69	-1.70	-0.34	-1.08	2.47

A more thorough harmonic analysis was also performed on the time series data from each gauging station in an effort to separate the various component signals which make up the observed tide. The analysis allows an understanding of the relative contribution that diverse physical processes (i.e. tides, winds, etc.) have on water level variations within the estuary. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 tidal constituents, with periods between 4 hours and 2 weeks, result from this procedure. The observed tide is therefore the sum of an astronomical tide component and a residual atmospheric component. The astronomical tide in turn is the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-7.

Table V-2 presents the amplitudes of eight significant tidal constituents. The M_2, or the familiar twice-a-day lunar semi-diurnal, tide is the strongest contributor to the signal with an amplitude of 1.4 feet in Nantucket Sound. The range of the M_2 tide is twice the amplitude, or about 2.8 feet. The diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar), possess amplitudes of approximately 0.43 and 0.34 feet respectively and account for the higher high tide followed by the lower low tide seen in figure V-5. The N_2 tide, a lunar constituent with a semi-diurnal period, is the next largest tidal constituent and is a little more then 3 times smaller then the main semi-diurnal constituent (M_2) with an amplitude of 0.45 feet. The M_4 tide, a higher frequency harmonic of the M_2 lunar tide (twice the frequency of the M_2), results from frictional dissipation of the M_2 tide in shallow water. The M_2 and N_2 have more influence on the shape of the tide signal than the other tidal constituents. The effect of the comparatively large amplitude can be seen most clearly in Figure V-5 as the semi-diurnal high and low tides.

Table V-2. Tidal Constituents, Lewis Bay System June 1 - July 21, 2004

AMPLITUDE (feet)								
	M2	M4	M6	S2	N2	K1	O1	Msf
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Nantucket Sound	1.41	0.15	0.07	0.09	0.45	0.43	0.34	0.06
Lewis Bay	1.45	0.14	0.08	0.09	0.46	0.43	0.33	0.07
Inner Harbor	1.44	0.14	0.09	0.10	0.46	0.43	0.33	0.06
Uncle Roberts Cove	1.45	0.14	0.09	0.10	0.46	0.43	0.33	0.06
Sweetheart Creek	1.45	0.14	0.09	0.10	0.46	0.44	0.34	0.06
Upper Mill Creek	1.40	0.09	0.06	0.08	0.42	0.42	0.33	0.09
Lower Mill Creek	1.40	0.12	0.06	0.08	0.42	0.41	0.33	0.08
Snows Creek	0.04	0.01	0.00	0.01	0.01	0.03	0.05	0.09

Table V-3 presents the phase delay (in other words, the travel time required for the tidal wave to propagate throughout the system) of the M_2 tide at all tide gauge locations inside the bay. The greatest delay occurs between the Nantucket Sound and Snows Creek gauging stations. There is a minor phase delay of the tide inside Lewis Bay between the main bay and the smaller fringing embayments. Mill Creek shows a great delay at both gauges which is a result of the inlet and narrow channels leading up into the creek. The degree of attenuation is not significant relative to the hydraulic efficiency of the system because the effects of attenuation are observed only in the phase delay across the system, and not as a reduction in the amplitude of the tide. The exception being Snows Creek which has a significant delay and reduction in amplitude.

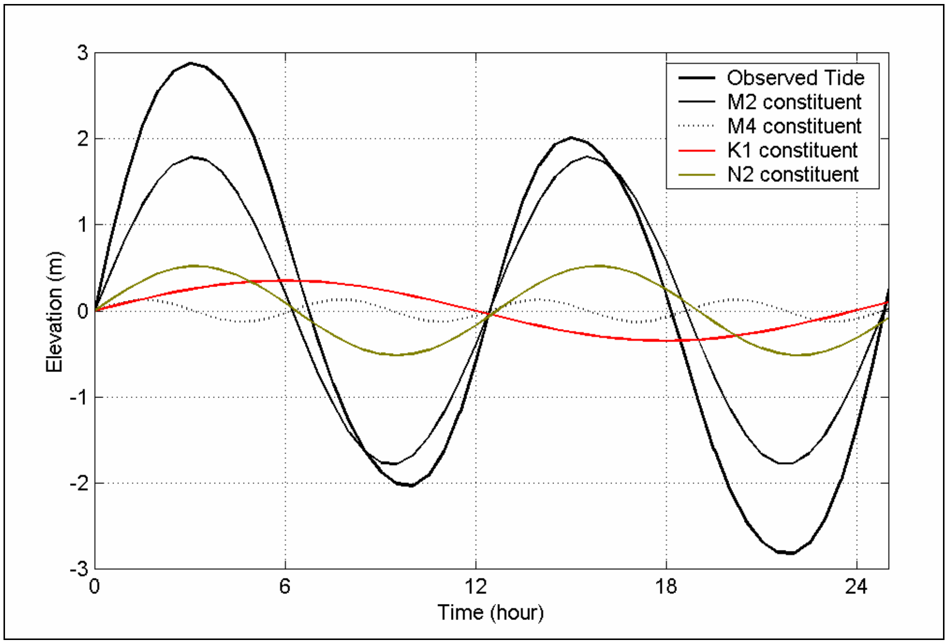


Figure V-7. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-3. M_2 Tidal Attenuation, Lewis Bay.	
June 1 – July 21 2004 (Delay in minutes relative to Nantucket Sound)	
Location	Delay (minutes)
Lewis Bay	5.024
Inner Harbor	5.045
Uncle Roberts Cove	5.665
Sweetheart Creek	5.273
Upper Mill Creek	12.482
Lower Mill Creek	10.229
Snows Creek	171.855

The tide data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. Non-tidal processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow. The results of an analysis to determine the energy distribution (or variance) of the original water elevation time series for the system is presented in Table V-4 compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 23 constituents determined by the harmonic analysis). Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes are relative to hydrodynamic circulation within the estuary. Figure V-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 percentage contribution of tidal energy was essentially equal in all parts of the system, which indicates that local effects due to winds and other non-tidal processes are minimal throughout the systems. The analysis also shows that tides are responsible for approximately 97% of the water level changes in Lewis Bay. The remaining 3% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of Nantucket Sound and Lewis Bay. The total energy content of the tide signal from each gauging station does not change significantly, nor does the relative contribution of tidal vs. non-tidal forces along the estuary basin. This is further indication that tide attenuation across the inlet and through the system is negligible. It is also an indication that the source of the non-tidal component of the tide signal is generated completely offshore, with no additional non-tidal energy input inside the system (e.g., from wind set-up of the pond surface). Snows Creek is the noted exception. It was shown to have a significant reduction in amplitude relative to Lewis Bay and this is again seen by a significant increase of non-tidal energy.

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

Table V-4. Percentages of Tidal versus Non-Tidal Energy, Lewis Bay, 2004

	Total Variance	Total	Tidal	Non-tidal
Unit	(ft^2)	(%)	(%)	(%)
Nantucket Sound	1.36	100	97.4	2.6
Lewis Bay	1.41	100	97.2	2.8
Inner Harbor	1.42	100	97.2	2.8
Uncle Roberts Cove	1.42	100	97.4	2.6
Sweetheart Creek	1.43	100	97.2	2.8
Upper Mill Creek	1.31	100	96.9	3.1
Lower Mill Creek	1.31	100	97.2	2.8
Snows Creek	0.02	100	46.6	53.4

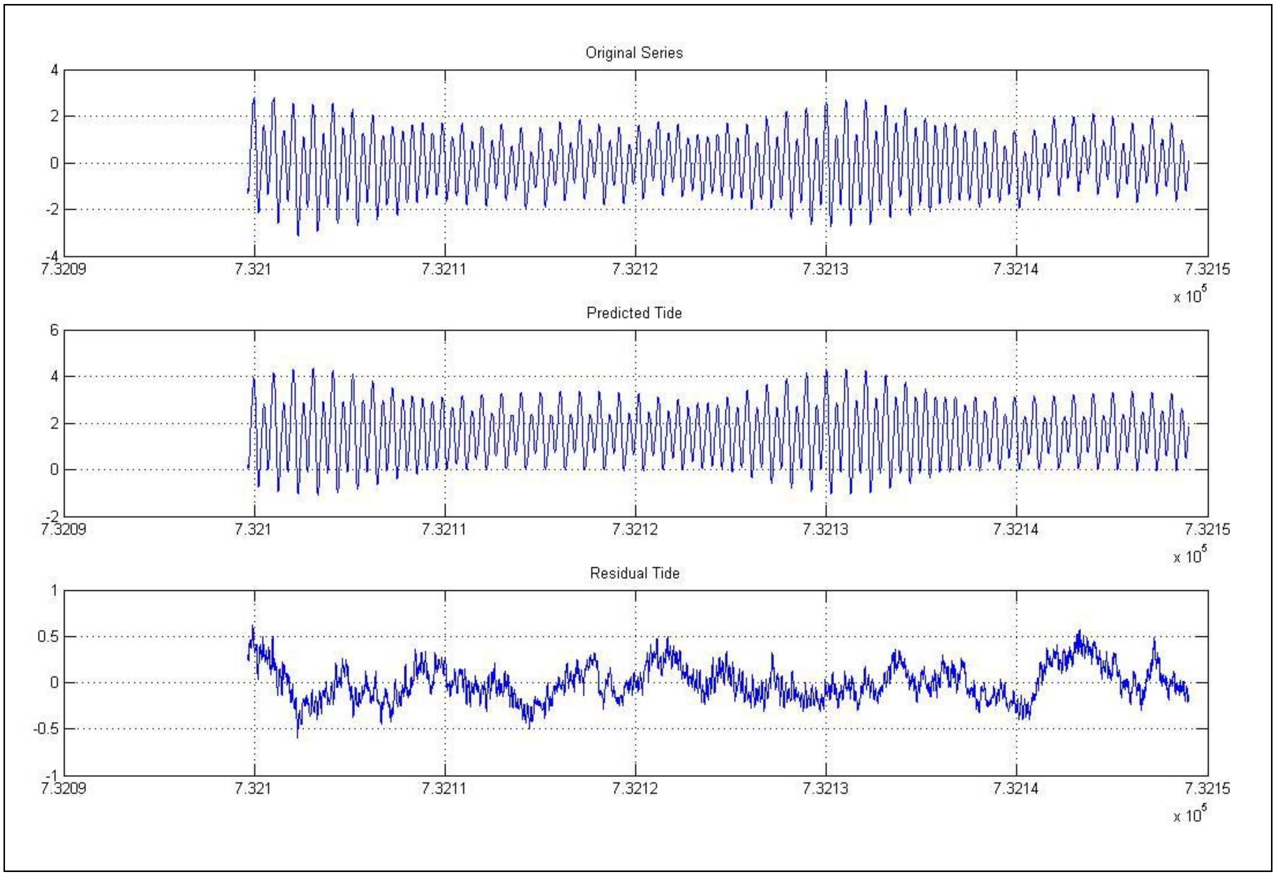


Figure V-8. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured in Nantucket Sound (LB1).

V.2.2.1 Halls Creek

Tide data records were collected at two locations for the Halls Creek analysis: offshore the Creek's inlet in Nantucket Sound and inside the Creek (see Figure V-4). The TDRs used to record the tide data were deployed for a 54-day period between May 27 and July 21, 2004. The elevation of each gauge was rectified relative to the NGVD 29 vertical datum. Duplicate offshore gauges were deployed to ensure data recovery, since the offshore tide record is crucial for developing the open boundary condition of the hydrodynamic model. Data collected by the gauge stationed inside the Creek were used in turn to calibrate and validate the hydrodynamic model.

Plots of the tide data from the tow tide stations used for this study are shown in Figure V-9, for the entire 54-day deployment. From the plot of the data from offshore Halls Creek, the maximum spring tide range of approximately 5.7 feet occurs June 3. About seven days later the neap tide range is much smaller, as small as 2.6 feet. The second spring tide should occur around June 17, at the time of the new moon, but the tide range is not clearly larger than seven days earlier during the spring tide range. The spring tides that occur during the full moon are easier to distinguish in the record.

The visual comparison in Figure V-10 between tide elevations measured in Nantucket Sound and inside the Creek shows that there is some decrease in the range of the tide through

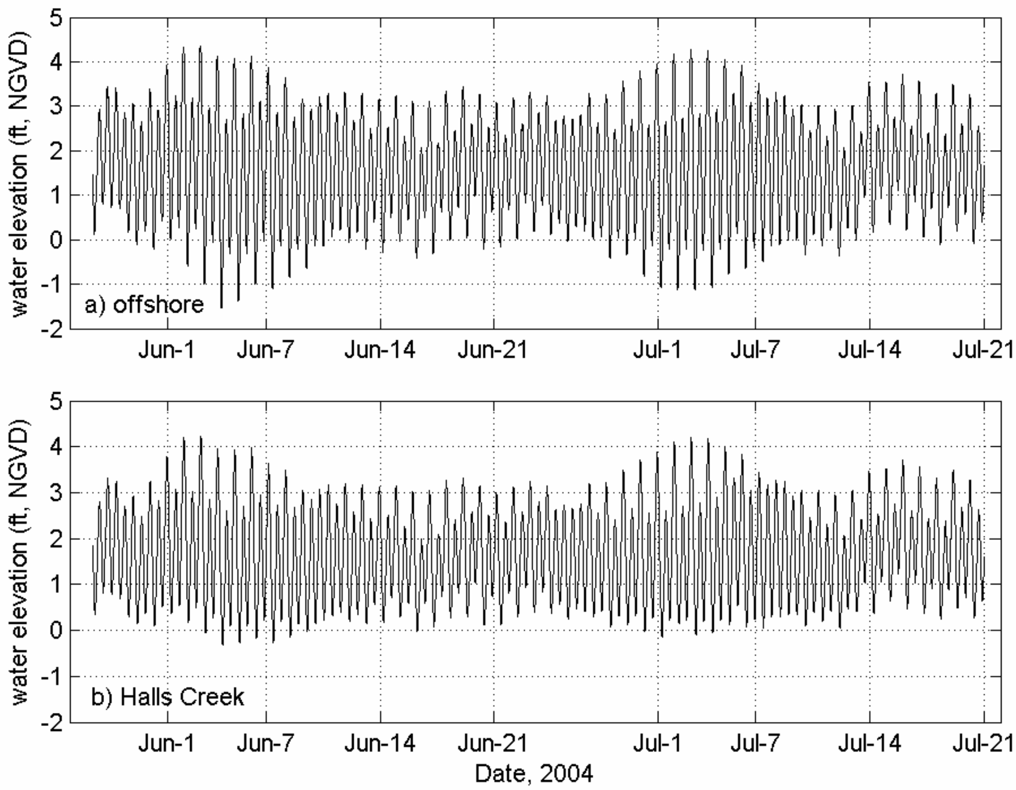


Figure V-9. Plots of observed tides for Halls Creek, for the 56-day period between May 27 and July 21, 2004. The top plot shows tides offshore Halls Creek inlet, in Nantucket Sound. The bottom plot shows the gauge record measured in Halls Creek. All water levels are referenced to NGVD 29.

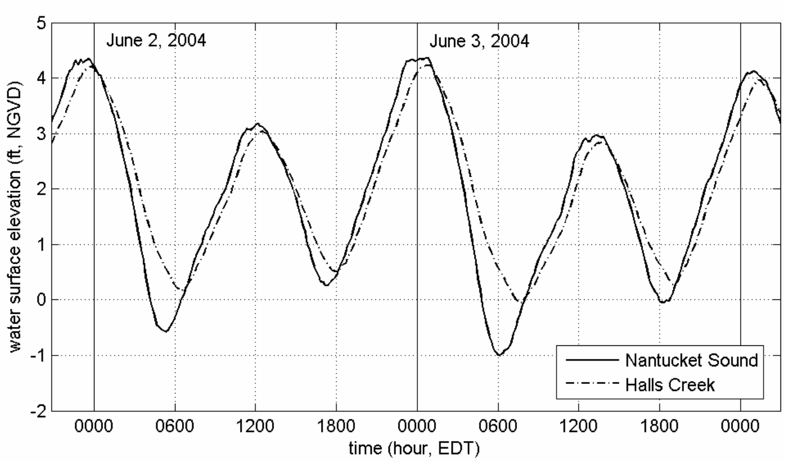


Figure V-10. Plot showing two tide cycles tides from the Halls Creek and Nantucket Sound tide data records, plotted together. Demonstrated in this plot is the minor frictional damping effect caused by flow restrictions at the inlets. The damping effects are seen only as a lag in time of high and low tides from Nantucket Sound. The maximum time lag of low tide between the Sound and Halls Creek in this plot is 103 minutes.

the system inlet. In Halls Creek, the low tide occurs approximately 100 minutes after low tide in Nantucket Sound. The delay at high tide is smaller, approximately 20 minutes.

The results of the analyses of the Hlas Creek tide data are presented in Tables V-2 and V-6. The standard tide are presented in Table V-5. Tide attenuation in Halls Creek through is apparent as an elevated MLW and MTL, compared to the offshore, which is typical of tides in marsh creeks. The results of the harmonic analysis of Halls Creek tides are presented in Table V-6. The harmonic analysis shows that the M_2 phase is shifted by 32 minutes compared to offshore. This means that the maximum and minimum elevations of the M_2 occur in Halls Creek 32 minutes after they have offshore.

Table V-5. Tide datums computed from a 28-day period from the tide records collected in the Halls Creek system. Datum elevations are given relative to NGVD 29.

Tide Datum	Offshore	Halls Creek
Maximum Tide	4.4	4.2
MHHW	3.4	3.3
MHW	3.1	3.0
MTL	1.5	1.6
MLW	0.0	0.3
MLLW	-0.4	0.1
Minimum Tide	-1.5	-0.3

Table V-6. Major tidal constituents determined for gauge locations in Halls Creek, May 27 through July 21, 2004.

	Amplitude (feet)							
Constituent	M_2	M_4	M_6	S_2	N_2	K_1	O_1	M_{sf}
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Nantucket Sound (offshore)	1.42	0.15	0.07	0.10	0.44	0.42	0.34	0.06
Halls Creek	1.21	0.06	0.04	0.07	0.34	0.39	0.31	0.09

Results of the residual analysis for Halls Creek are presented in Figure Table V-7 and V-11. Table V-7 shows a reduction in the variance of tidal energy between the offshore tide and the tide measured inside Halls Creek. The analysis also shows that tides are responsible for approximately 96% of the water level changes in the Creek. The remaining 4% was the result of atmospheric forcing, due to winds, or barometric pressure gradients. Figure V-11 shows the comparison of the measured tide in Halls Creek, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

Table V-7. Percentages of Tidal versus Non-Tidal Energy for Halls Creek gauging stations, May to July, 2004.

TDR LOCATION	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Nantucket Sound (offshore)	1.34	96.9	3.1
Halls Creek	0.97	96.4	3.6

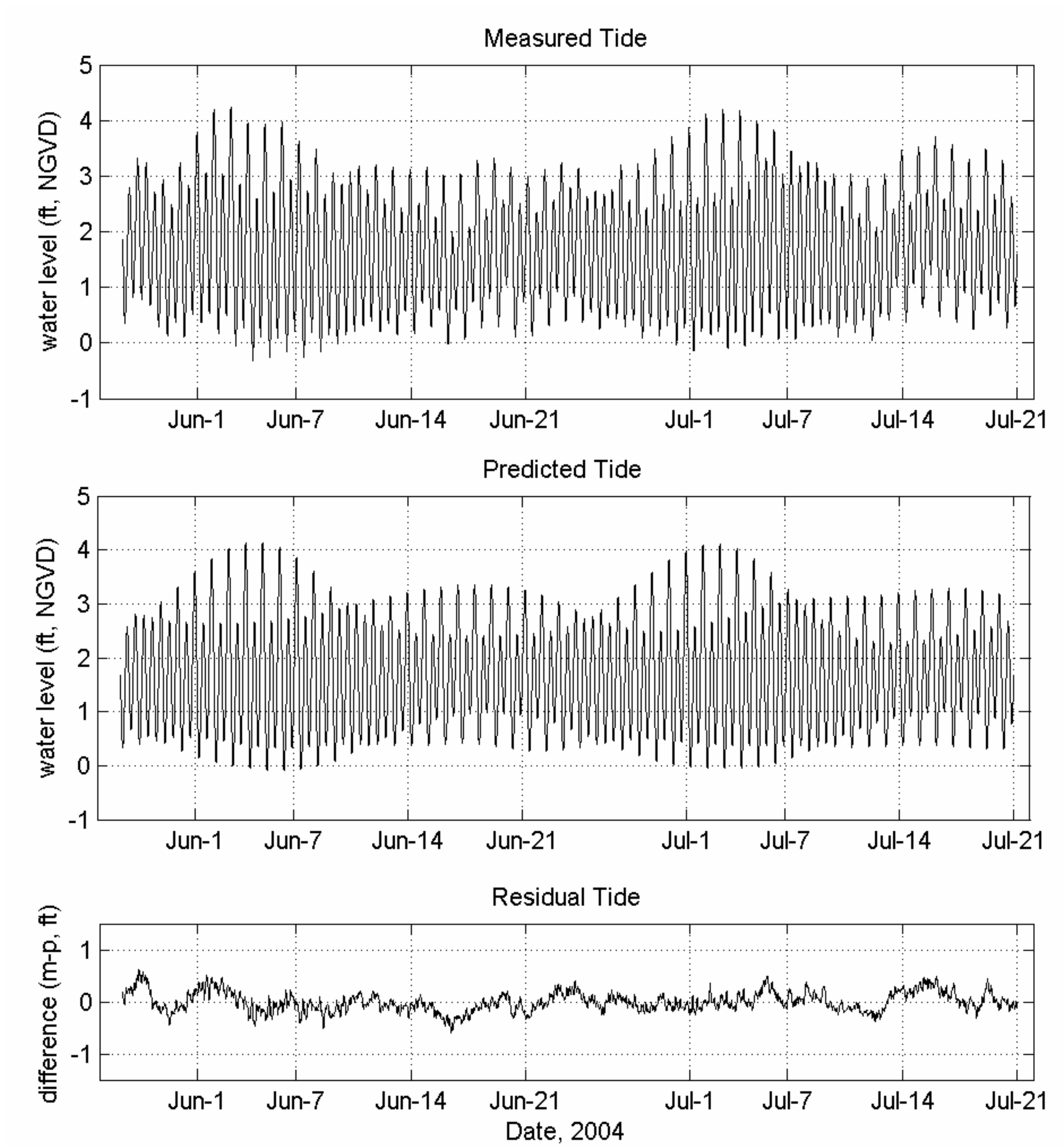


Figure V-11. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 23 individual tide constituents determine in the harmonic analysis of the Halls Creek gauge data. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (r=m-p).

V.2.3 ADCP Data Collection and Analysis

The measurements were collected using an Acoustic Doppler Current Profiler (ADCP) mounted aboard a small survey vessel. The boat repeatedly navigated a pre-defined set of transect lines through the area, approximately every 60 minutes, with the ADCP continuously collecting current profiles. This pattern was repeated for an approximate 13-hour duration to ensure measurements over the entire tidal cycle. The results of the data collection effort are high-resolution observations of the spatial and temporal variations in tidal current patterns throughout the survey area.

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

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

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

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

Current measurements were collected by the ADCP as the vessel navigated repeatedly a series of two (2) pre-defined transect lines in Lewis Bay (Figure V-2). The line-cycles were repeated every hour throughout the survey. The first cycle was begun at 07:27 hours (Eastern

Daylight Time, EDT) and the final cycle was completed at 20:42 hours (EDT), for a survey duration of approximately 13 hours on June 23, 2004.

The transect lines A-1 and A-3 were run in ascending order. These lines were designed to measure as accurately as possible the volume flux through the constrictions during a complete tidal cycle. Line A-1 ran across the entrance to Lewis Bay between Kalmus Park and Smith's Point. Line A-3 ran across the inlet to Mill Cove.

V.3 HYDRODYNAMIC MODELING

The focus of this study was the development of a numerical model capable of accurately simulating hydrodynamic circulation within the Lewis Bay estuary and Halls Creek marsh system. Once calibrated, the model was used to calculate water volumes for selected subembayments (e.g., the Inner Hyannis Harbor, Mill Creek, Sweetheart Creek, etc.) as well as determine the volumes of water exchanged during each tidal cycle. These parameters are used to calculate system residence times, or flushing rates. The ultimate utility of the hydrodynamic model is to supply required input data for the water quality modeling effort described in Chapter VI.

V.3.1 Model Theory

Thie analyses of Lewis Bay and Halls Creek each utilized a state-of-the-art computer model to evaluate tidal circulation and flushing. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2 for numerous flushing studies for estuary systems in southeast Massachusetts, including Falmouth's 'finger' ponds, Centerville River, and Popponesset Bay.

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

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

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

V.3.2.1 Grid Generation

The finite element grid for each system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties within the estuary. Fine resolution is required to simulate the numerous channel constrictions (e.g., entrance to Mill Creek) that significantly impact the estuarine hydrodynamics. Grid resolution is governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each region. Smaller cross channel node spacing in the marsh channels was designed to provide a more detailed analysis in these regions of rapidly varying velocities and bathymetry. Widely spaced nodes were utilized in areas where velocity gradients were likely to be less acute; for example, on marsh plains and in broad, deep channel sections in the model domain. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

The grid generation process for the models was assisted through the use of the SMS package. The digital shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary with a number of computational elements. For Lewis Bay, 2295 elements, defined by 5660 computational nodes, were used to represent the system. In Halls Creek, the completed grid consists of 8,474 nodes, which describe 3,304 total elements. All regions in the system were represented by two-dimensional (depth-averaged) elements.

The completed grid is made up of quadrilateral and triangular two-dimensional elements. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the recent field surveys and the NOS data archive. The mesh of Lewis Bay is shown in Figure V-12, and the interpolated grid bathymetry is shown in Figure V-13. The completed grid mesh of Halls Creek is shown in Figure V-14, and grid bathymetry is shown in Figure V-15.

V.3.2.2 Boundary Condition Specification

Three types of boundary conditions were employed for the RMA-2 model: 1) "slip" boundaries, and 2) tidal elevation boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations

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

V.3.3 Calibration

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

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

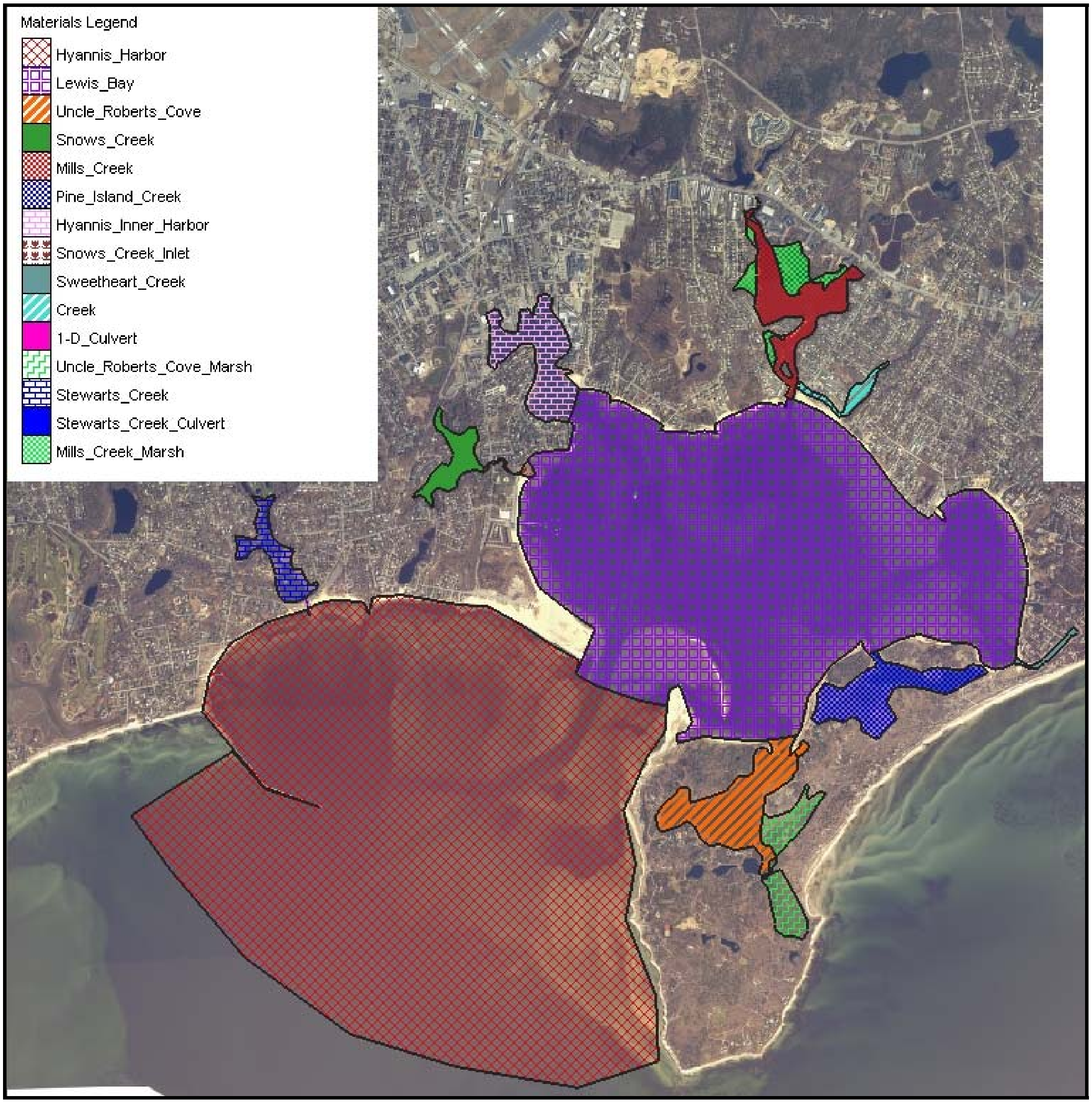


Figure V-12. The model finite element mesh developed for Lewis Bay estuary system. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained in Nantucket Sound.

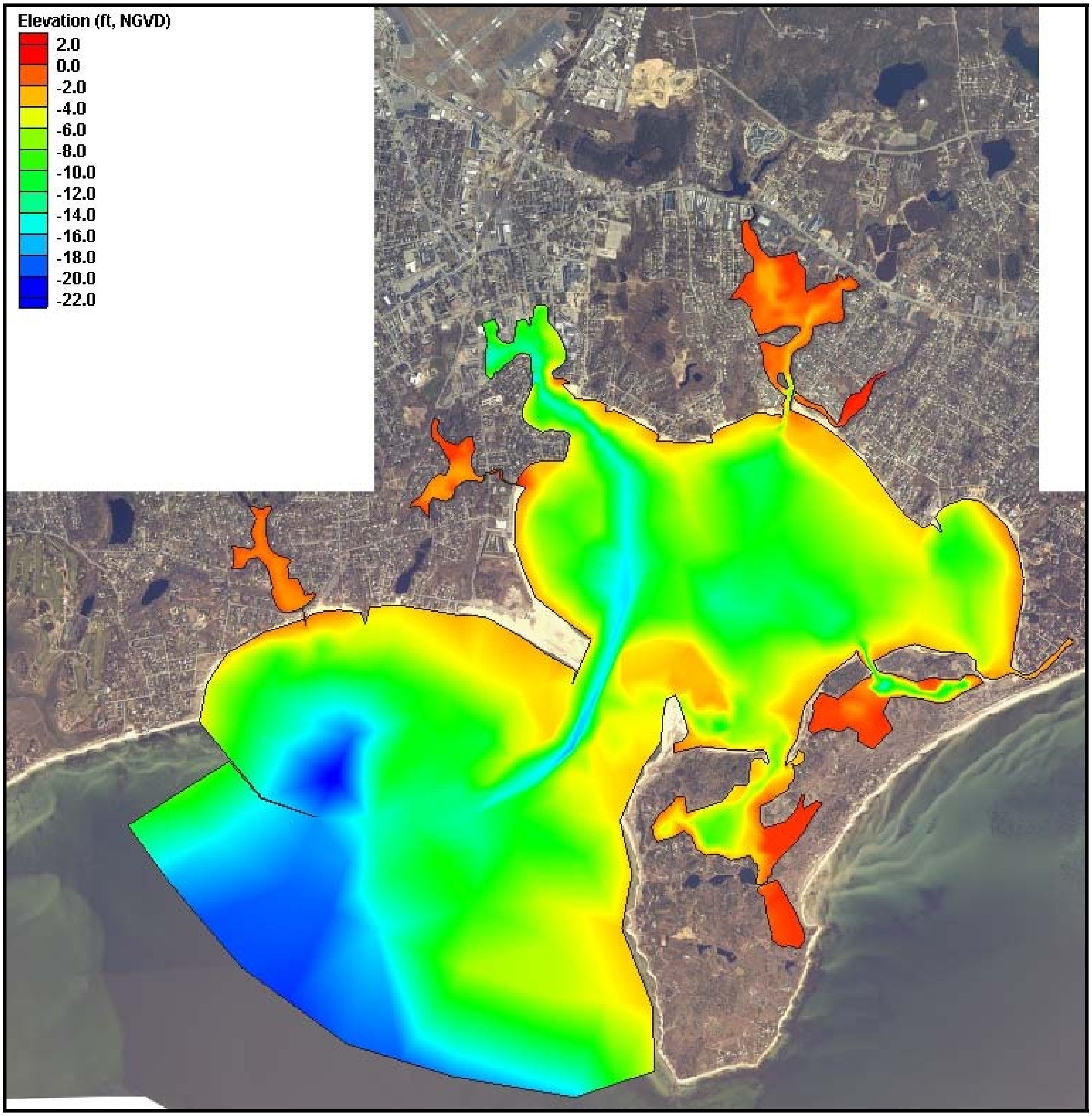


Figure V-13. Depth contours of the completed Lewis Bay finite element mesh.

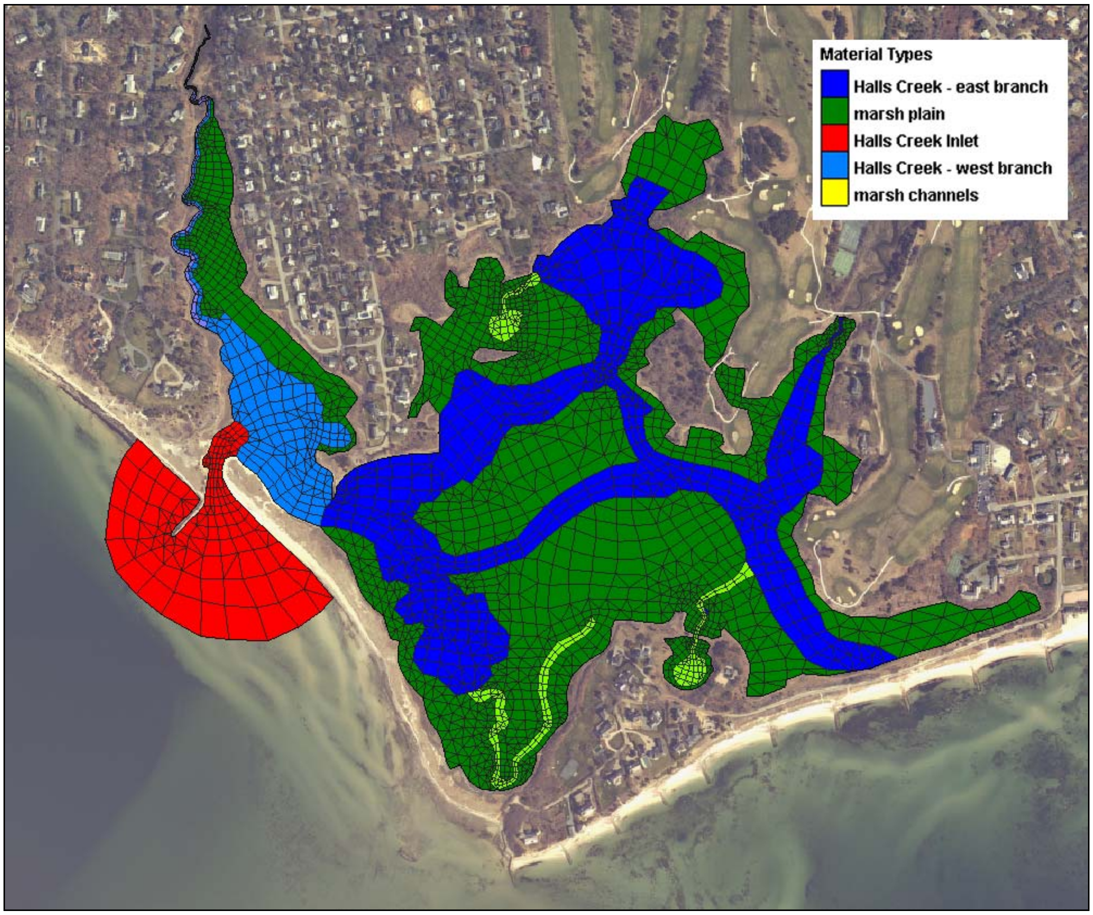


Figure V-14. Plot of hydrodynamic model grid mesh for Halls Creek. Colors designate the different model material types used to vary model calibration parameters and compute flushing rates.

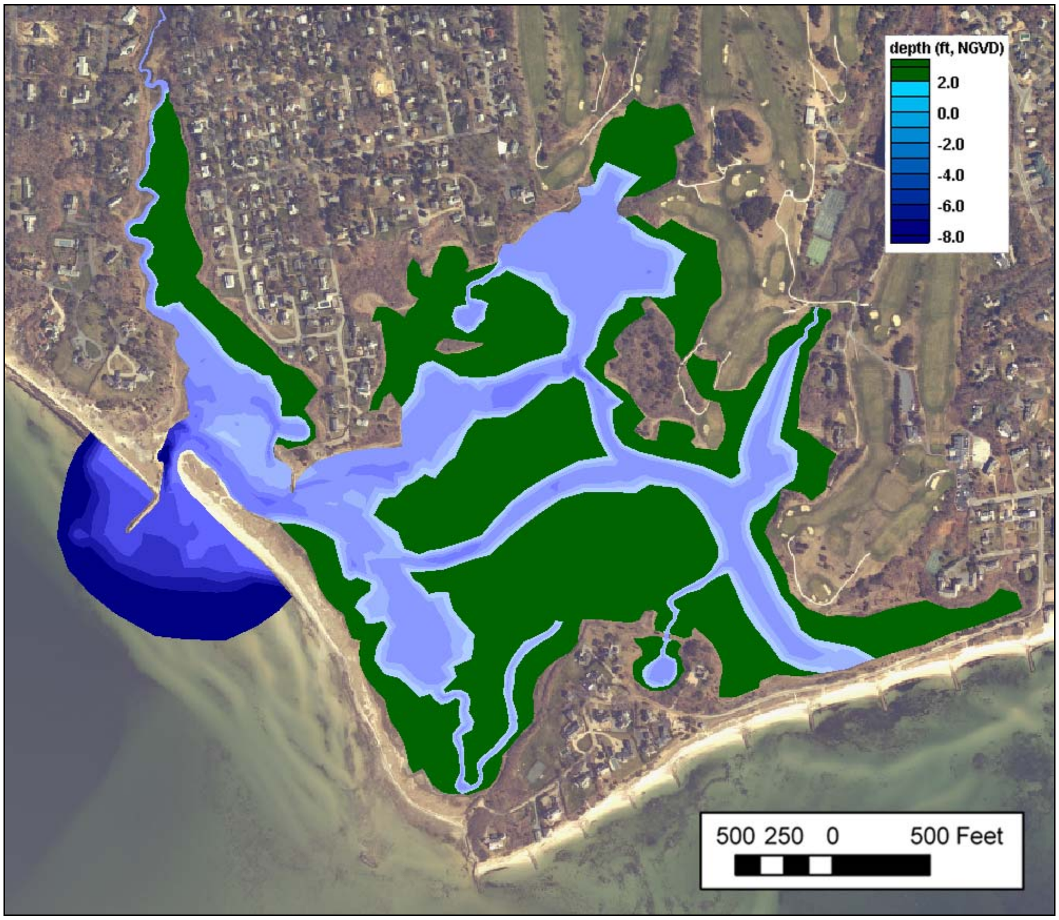


Figure V-15. Plot of interpolated finite-element grid bathymetry of the Halls Creek system, shown superimposed on 2005 aerial photos of the system locale. Bathymetric contours are shown in color at one-foot intervals.

For Lewis Bay, the calibration was performed for an approximate eight-day period, beginning 2000 hours EDT June 1, 2004 and ending 2000 EDT June 9, 2004. For Halls Creek, the calibration was performed for a five-day period beginning July 3, 2004 at 1200 EDT. These time periods include a 12-hour model spin-up period. This representative time periods were selected for each model because they included tidal conditions where the wind-induced portion of the signals (i.e. the residual) was minimal, hence more typical of tidal circulation within the estuary. The selected time periods also spanned the transition from spring (bi-monthly maximum) to neap (bi-monthly minimum) tide ranges, which is representative of average tidal conditions in the embayment system. For Lewis Bay, the selected 7.75 day simulation period, the tide ranged approximately 5.8 feet from minimum low to maximum high tides. At Halls Creek, the maximum tide range during the simulation is 5.3 feet. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. Modeled tides were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated models were used to analyze existing detailed flow patterns and compute residence times.

V.3.3.1 Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where water depths can become shallow and velocities relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude attenuation and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient. First, Manning's friction coefficient values of 0.025 were specified for all elements in each model. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels with pools and shoals with higher friction (Henderson, 1966). On the marsh plains of Mill Creek and Halls Creek, damping of flow velocities typically is controlled more by "form drag" associated with marsh plants than the bottom friction described above. However, simulation of this "form drag" is performed using Manning's coefficients as well, with values ranging from 2-to-10 times friction coefficients used in sandy channels. Final calibrated friction coefficients (listed in Table V-8 for Lewis Bay and Halls Creek) were largest for marsh plain area, where values were set at between 0.033 and 0.070. Small changes in these values did not change the accuracy of the calibration.

Table V-8. Manning's Roughness coefficients used in simulations of modeled systems.

Embayment	Bottom Friction
Lewis Bay and Hyannis Harbor	
Hyannis Harbor	0.024
Lewis Bay	0.024
Uncle Roberts Cove	0.025
Uncle Roberts Cove (marsh)	0.033
Snows Creek	0.030
Pine Island Creek	0.027
Mill Creek	0.026
Mill Creek (marsh)	0.030
Mill Creek (creek on eastern edge)	0.026
Mill Creek (culvert)	0.025
Hyannis Inner Harbor	0.025
Snows Creek Inlet	Varies
Sweetheart Creek	0.025
Stewarts Creek	0.025
Stewarts Creek (culvert)	0.035
Halls Creek	
Halls Creek - east branch	0.025
Marsh plain	0.070
Halls Creek inlet	0.035
Halls Creek - west branch	0.035
Marsh channels	0.025

V.3.3.2 Turbulent Exchange Coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swift, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). The model was mildly sensitive to turbulent exchange coefficients, with areas of marsh plain being most sensitive. In other regions where the flow gradients were not as strong, the model was much less sensitive to changes in the turbulent exchange coefficients. Typically, model turbulence coefficients (D) are set between 20 and 200 lb-sec/ft^2 (as listed in Table V-9). Higher values (up to 500 lb-sec/ft^2) are used on the marsh plain, to ensure solution stability.

Table V-9. Turbulence exchange coefficients (D) used in simulations of the modeled embayment systems.	
Embayment	D (lb-sec/ft^{2})
Lewis Bay and Hyannis Harbor	
Hyannis Harbor	50
Lewis Bay	75
Uncle Roberts Cove	70
Uncle Roberts Cove (marsh)	120
Snows Creek	50
Pine Island Creek	75
Mill Creek	75
Mill Creek (marsh)	75
Mill Creek (creek on eastern edge)	70
Mill Creek (culvert)	60
Hyannis Inner Harbor	60
Snows Creek Inlet	100
Sweetheart Creek	100
Stewarts Creek	100
Stewarts Creek (culvert)	150
Halls Creek	
Halls Creek - east branch	200
Marsh plain	200
Halls Creek inlet	100
Halls Creek - west branch	100
Marsh channels	20

V.3.3.3 Wetting and Drying/Marsh Porosity Processes

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

V.3.3.4 Comparison of Modeled Tides and Measured Tide Data

Several calibration model runs were performed for each system to determine how changes to various parameters (e.g. friction and turbulent exchange coefficients) affected the model results. These trial runs achieved excellent agreement between the model simulations and the field data.

V.3.3.4.a Lewis Bay

Comparison plots of modeled versus measured water levels in Lewis Bay, at the eight gauge locations, is presented in Figures V-15 through V-22. At all gauging stations RMS errors were less than 0.16 ft (<2.0 inches) and computed R^2 correlation was better than 0.99. Errors between the model and observed tide constituents were less than 0.06 inch for all locations, suggesting the model accurately predicts tidal hydrodynamics within the Lewis Bay system. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the calibration time period are shown in Table V-7. The constituent values in for the calibration time period differ from those in

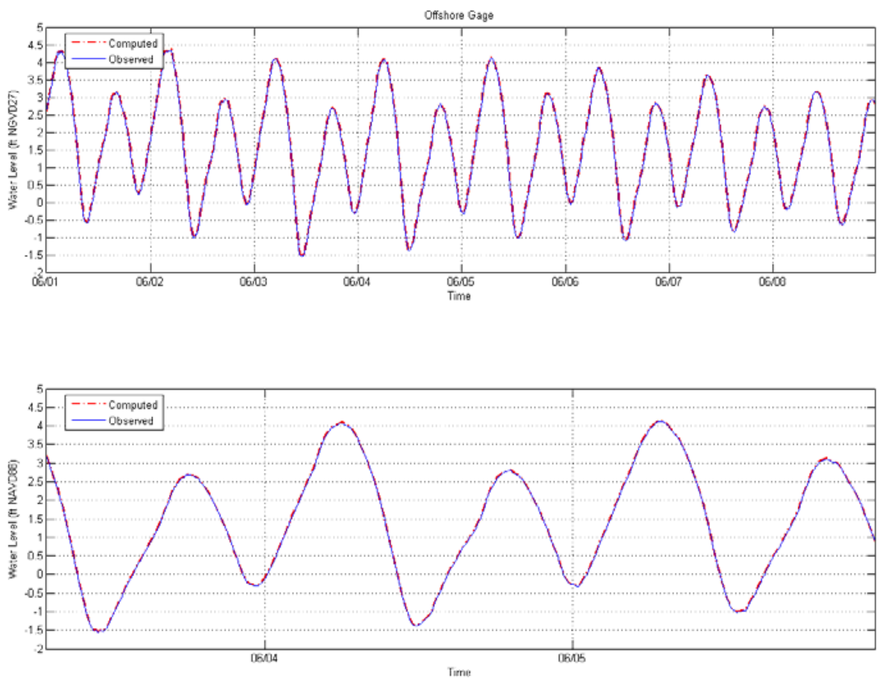


Figure V-15. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the calibration time period, for the offshore gauging station. The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

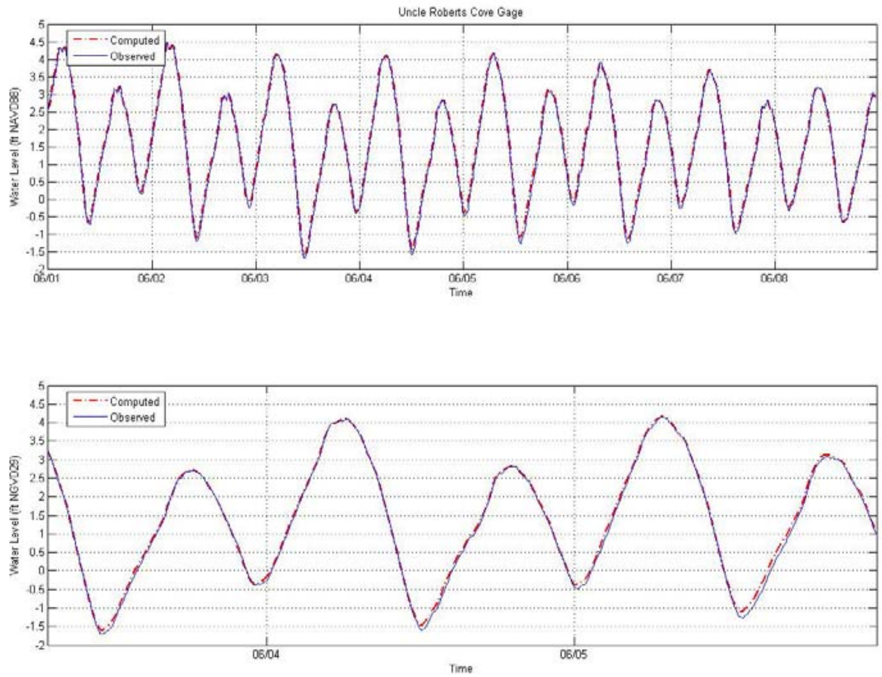


Figure V-16. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Uncle Roberts Cove gauging station (LB2). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

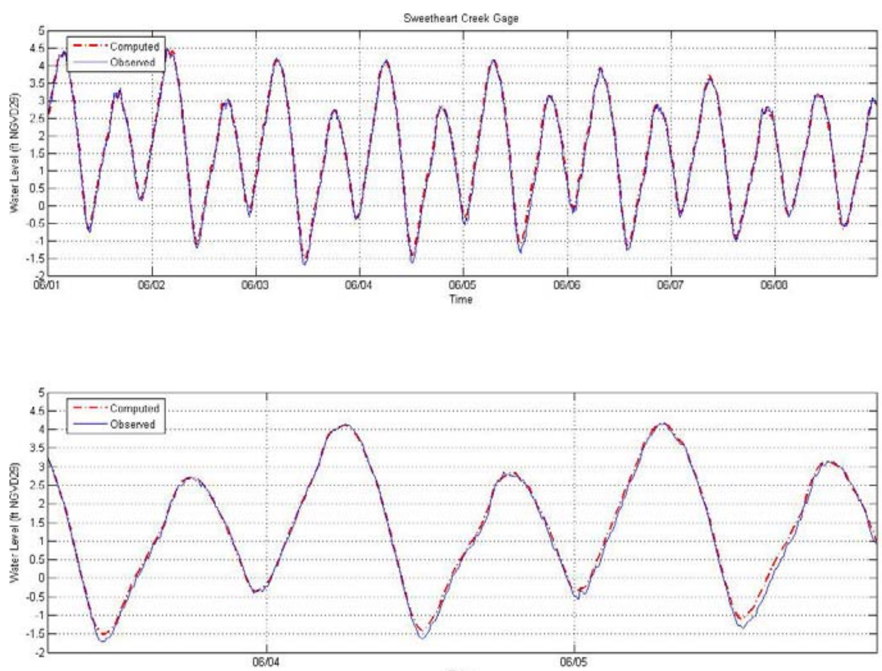


Figure V-17. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Sweetheart Creek gauging station (LB3). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

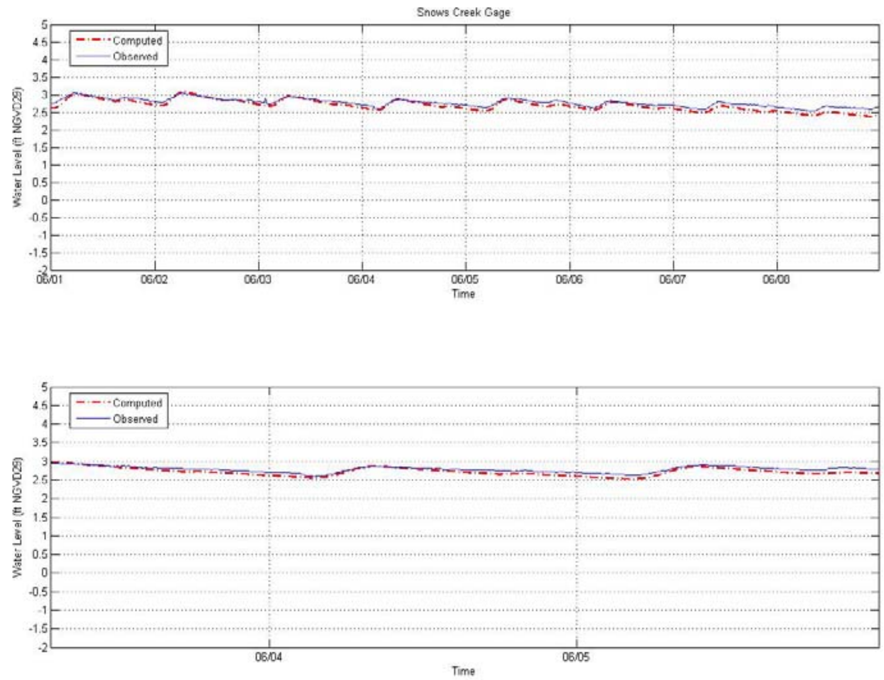


Figure V-18. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Snows Creek gauging station (LB4). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

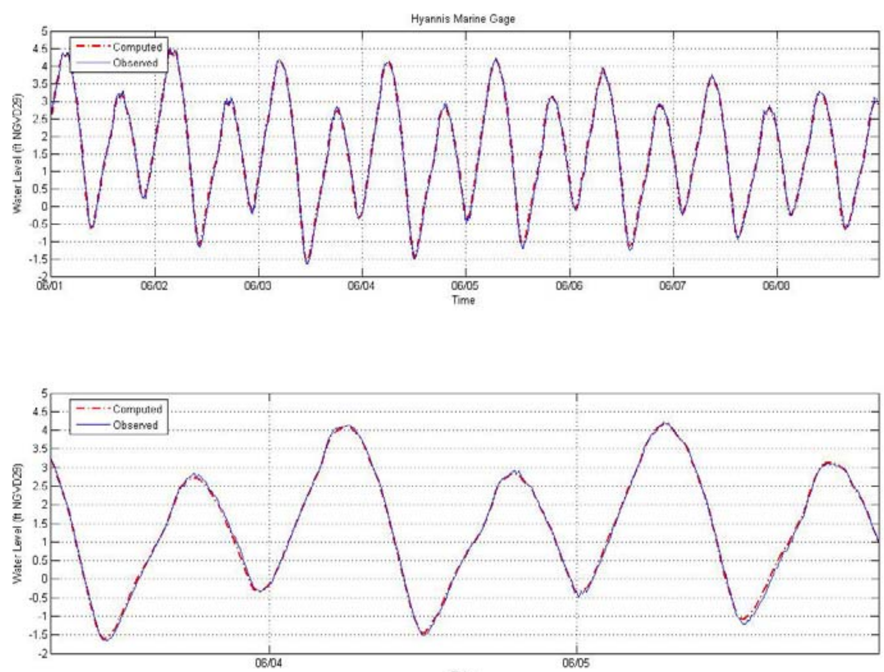


Figure V-19. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Hyannis Inner Harbor gauging station (LB5). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

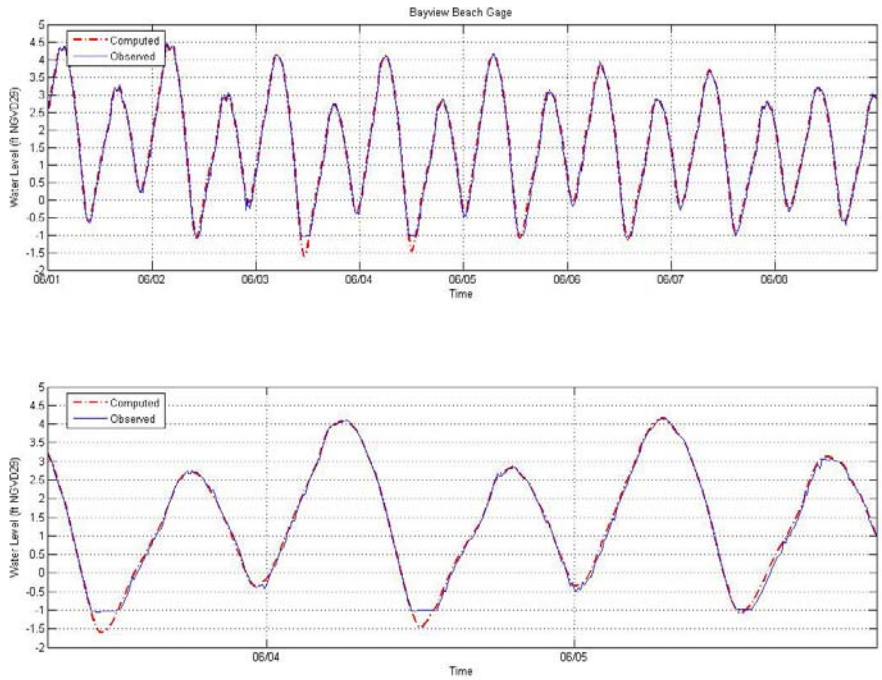


Figure V-20. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period for the Lewis Bay gauging station (LB6). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

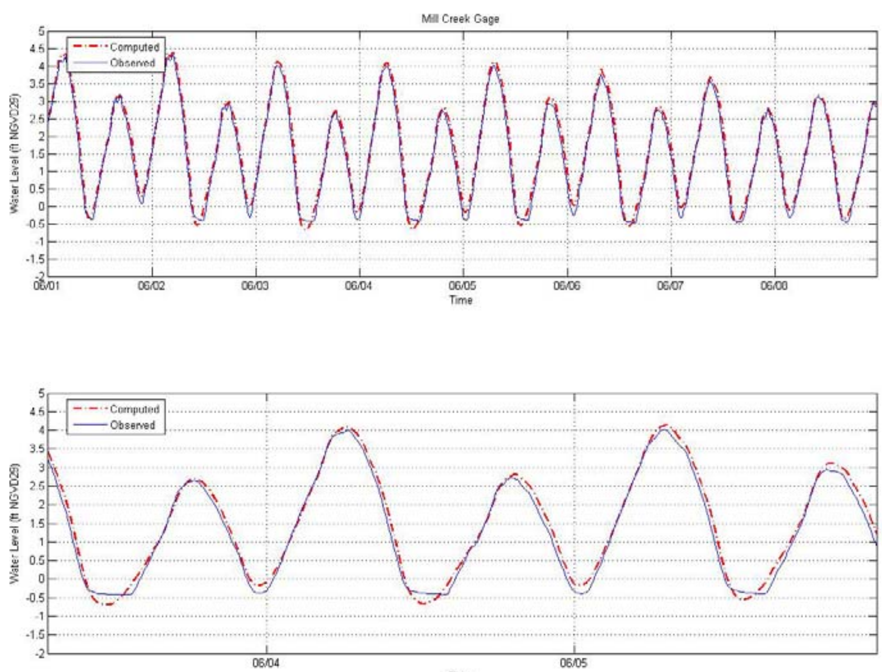


Figure V-21. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Lower Mill Creek gauging station (LB7). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

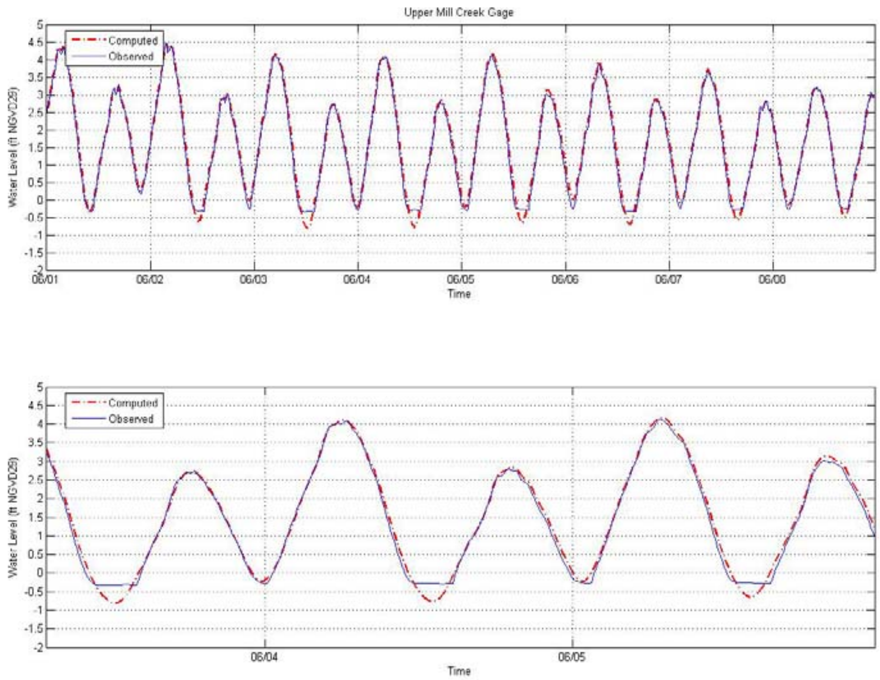


Figure V-22. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Upper Mill Creek gauging station (LB8). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

Tables V-2 because constituents were computed for only 7.75 days, rather than the entire 55-day period represented in Tables V-2. Errors associated with tidal constituent height were on the order of hundredths of feet, which was an order of magnitude better than the accuracy of the tide gage gauges (±0.12 ft). Time lag errors were less than the time increment resolved by the model and measured tide data (1/6 hours or 10 minutes), indicating good agreement between the model and data.

Table V-10. Comparison of tidal constituents from the calibrated RMA2 model of Lewis Bay versus measured tidal data for the period June 1 to June 8, 2004.

Model Verification Run						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Nantucket Sound	1.88	0.23	0.11	0.67	94.42	-60.33
Lewis Bay	1.89	0.22	0.13	0.67	96.34	-48.26
Inner Harbor	1.89	0.22	0.13	0.67	96.39	-48.01
Uncle Roberts Cove	1.89	0.21	0.13	0.68	96.92	-45.63
Sweetheart Creek	1.89	0.21	0.13	0.68	96.83	-45.67
Upper Mill Creek	1.79	0.07	0.07	0.65	104.35	25.91
Lower Mill Creek	1.78	0.19	0.09	0.63	103.88	-59.47
Snows Creek	0.07	0.02	0.00	0.08	-171.56	-66.63
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Nantucket Sound	1.86	0.22	0.11	0.65	1.68	-0.93
Lewis Bay	1.88	0.18	0.11	0.65	99.38	-39.59
Inner Harbor	1.90	0.20	0.13	0.66	99.24	-34.82
Uncle Roberts Cove	1.90	0.20	0.13	0.66	99.59	-32.50
Sweetheart Creek	1.90	0.20	0.13	0.66	99.48	-34.23
Upper Mill Creek	1.75	0.08	0.05	0.60	103.75	-96.68
Lower Mill Creek	1.76	0.14	0.06	0.60	102.44	-75.09
Snows Creek	0.05	0.01	0.00	0.05	-175.24	-85.07
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Nantucket Sound	-0.02	-0.02	-0.01	-0.01	3.95	7.50
Lewis Bay	-0.03	-0.01	-0.04	-0.02	6.30	8.98
Inner Harbor	-0.02	0.01	-0.02	0.00	5.88	13.66
Uncle Roberts Cove	-0.02	0.01	-0.02	0.00	5.53	13.59
Sweetheart Creek	-0.01	0.01	-0.01	0.00	5.49	11.85
Upper Mill Creek	-0.06	-0.04	0.01	-0.02	-1.23	-126.9
Lower Mill Creek	-0.03	-0.01	-0.05	-0.03	-3.00	-16.17
Snows Creek	-0.03	-0.02	0.00	0.00	-7.61	-19.08

V.3.3.4.b Halls Creek Calibration

A best-fit of model predictions for the TDR deployment was achieved using the aforementioned values for friction and turbulent exchange. Figures V-23 and V-24 illustrate the five-day calibration simulation along with a 50-hour sub-section. 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 and maximize the accuracy of the models. Calibration of M_2 (principle lunar semidiurnal constituent) was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled system. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1,

M_2, M_4, and M_6. Measured tidal constituent heights (H) and time lags (ϕ_{lag}) shown in Table V-11 for the calibration period differ from those in Table V-11 because constituents were computed for only the five-day section of the 31-days represented in Table V-6. Table V-6 compares tidal constituent amplitude (height) and relative phase (time) for modeled and measured tides at the TDR locations. The constituent phase shows the relative timing of each separate constituent at a particular location, and also the change (or phase lag) in timing of a single constituent at different locations in an estuary.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.01 ft, which is better than the accuracy of the tide gauges (±0.12 ft). Time lag errors were typically less than the time increment resolved by the model (1/6 hours or 10 minutes), indicating good agreement between the model and data.

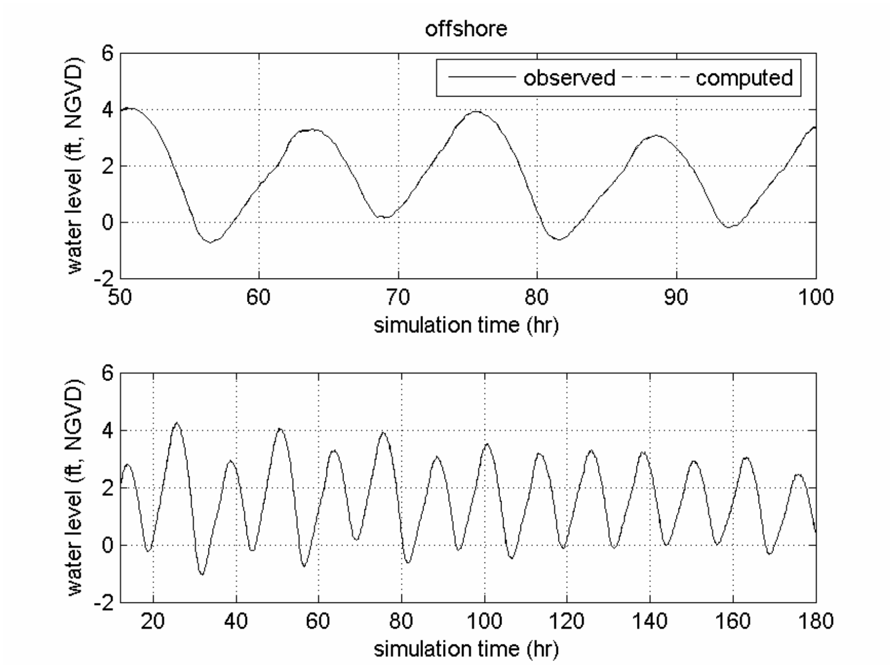


Figure V-23. Comparison of model output and measured tides for the TDR location offshore Hyannisport, in Nantucket Sound for the modeled calibration period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

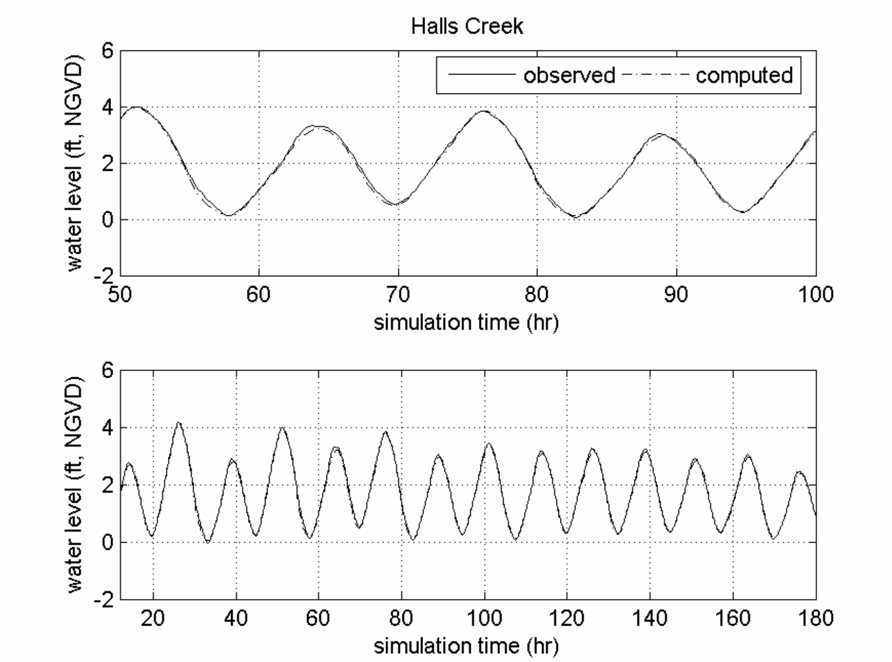


Figure V-24. Comparison of model output and measured tides for the TDR location in Halls Creek, for the modeled calibration period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

Table V-11. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for Halls Creek, during modeled calibration time period.

Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	1.78	0.22	0.09	0.45	49.9	206.6
Halls Creek	1.50	0.10	0.02	0.41	66.8	210.8
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	1.80	0.22	0.10	0.45	51.0	211.8
Halls Creek	1.49	0.06	0.05	0.41	68.4	207.2
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	0.02	0.00	0.01	0.00	2.3	5.4
Halls Creek	-0.01	-0.04	0.03	0.00	3.3	-3.7

V.3.3.4.c Halls Creek Tidal Verification

An additional verification model run was performed to further test the calibrated model. This step was performed for Halls Creek, unlike for the Lewis Bay Model, since ADCP data were not available for verification. Similar to the calibration procedure, tides for five-day period starting June 2, 2004 at 1200 EDT were simulated with model. However, for the verification run, the friction and eddy viscosity coefficients, set during the model calibration process, were not modified. A comparison of tidal constituents from modeled and measured tides is presented in Table V-12. Plots of model output from the model calibration are presented in Figures V-25 and V-26. Similar to the calibration, errors in amplitude and phase of the extracted constituents are small and within the resolution of the instrument. The results of the verification provide further assurance of the skill of the model's calibration.

V.3.4 ADCP verification of the Lewis Bay system

An additional model verification check was possible by using collected ADCP velocity data to verify the performance of the model in representing the system dynamics. Computed flow rates from the model were compared to flow rates determined using the measured velocity data. The ADCP data survey efforts are described in Section V.2.3. For the model ADCP verification, the Lewis Bay model was run for the period covered during the ADCP survey on June 23, 2004.

The verification model period was performed for an approximate eight-day period, beginning 0000 hours EDT June 20, 2004 and ending 0000 EDT June 28, 2004. This time period included a 12-hour model spin-up period, and a tide cycle period used to compare to the ADCP data. Model flow rates were computed in RMA-2 at continuity lines (channel cross-sections) that correspond to the actual ADCP transects followed in the survey across the three locations in the Bay.

Table V-12. Tidal constituents for measured water level data and model output, with model error amplitudes, for Halls Creek, during modeled validation time period.

Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	1.90	0.24	0.10	0.79	3.8	116.5
Halls Creek	1.53	0.12	0.03	0.68	21.4	94.2
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	1.93	0.25	0.11	0.80	4.8	120.6
Halls Creek	1.50	0.09	0.06	0.68	24.0	81.3
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Nantucket Sound	0.03	0.01	0.01	0.01	2.1	4.2
Halls Creek	-0.03	-0.03	0.03	0.00	5.4	-13.4

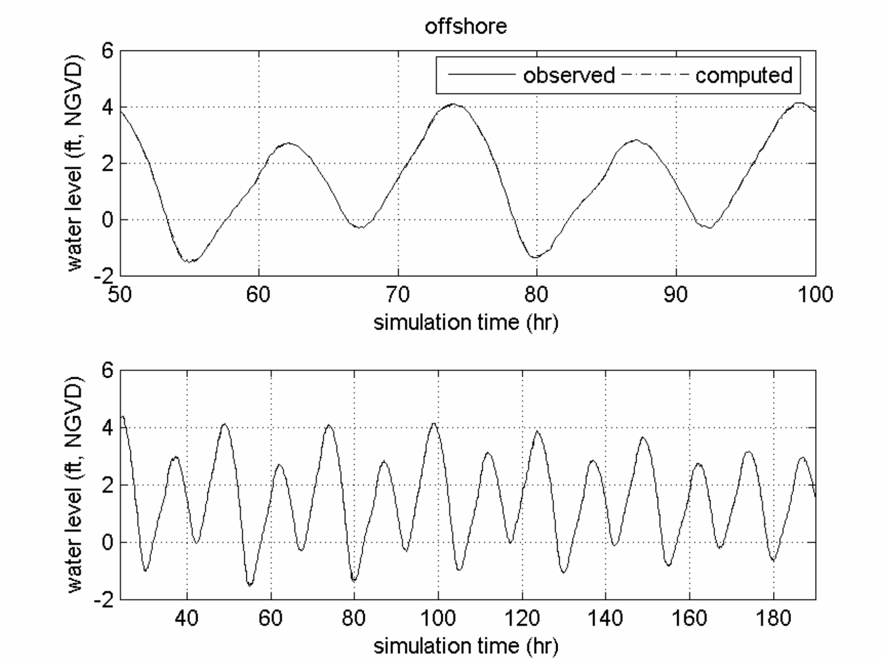


Figure V-25. Comparison of model output and measured tides for the TDR location offshore Hyannisport, in Nantucket Sound, for the modeled verification period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

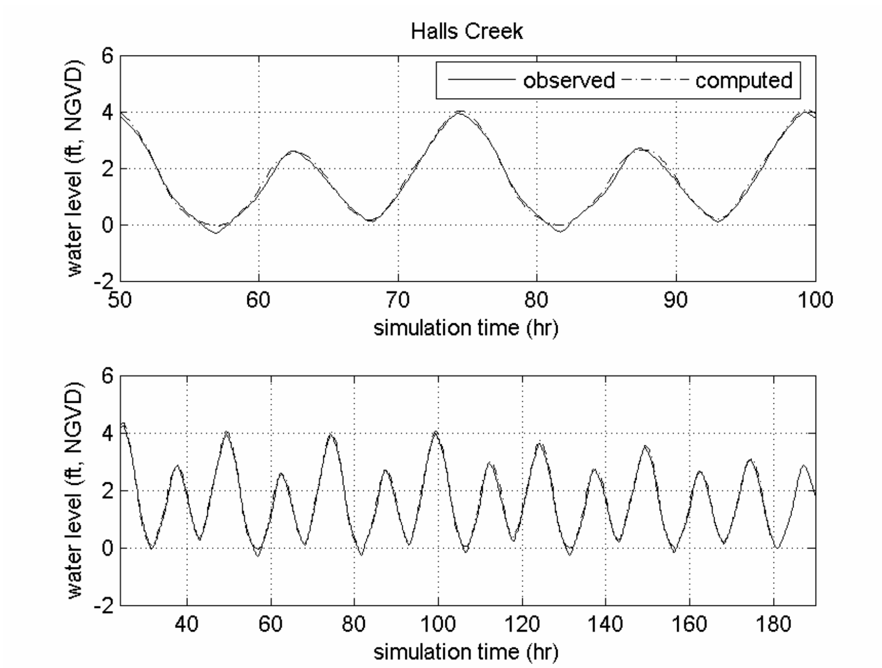


Figure V-26. Comparison of model output and measured tides for the TDR location in Halls Creek, for the modeled verification period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

Data comparisons at the Lewis Bay ADCP transects show good agreement with the model predictions, with R^2 correlation coefficients between data and model results range from 0.84 to 0.91. A comparison of the measured and modeled volume flow rates at the survey transect are shown in Figures V-27 and V-28. The top plot in the figure shows the flow comparison, and the lower plot shows the time series of tide elevations for the same period. Each ADCP point (black circles shown on the plots) is a summation of flow measured along the ADCP transect at a discrete moment in time. The 'bumps' and 'skips' of the flow rate curve (more evident in the model output) can be attributed mostly to the peculiar nature of the forcing tide in this region, but also to the effects of winds (i.e., atmospheric effects) on the water surface and friction across the seabed periodically retarding or accelerating the flow through the inlets. If water surface elevations changed smoothly as a sinusoid, the volume flow rate would also appear as a smooth curve. However, since the rate at which water surface elevations change does not vary smoothly, the flow rate curve is expected to show short-period fluctuations.

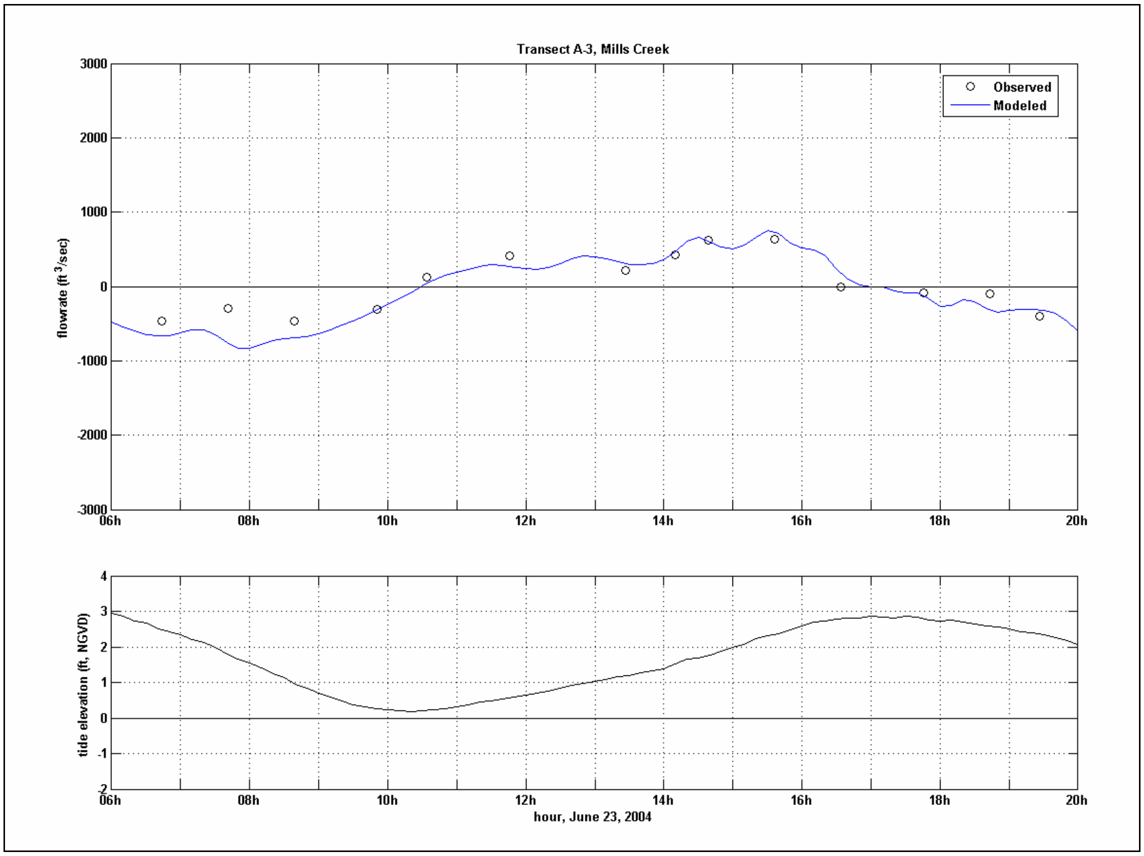


Figure V-27. Comparison of measured volume flow rates versus modeled flow rates (top plot) across Mill Creek inlet transect (A-3), over a tidal cycle on June 23, 2004 (R^2 = 0.84). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Nantucket Sound.

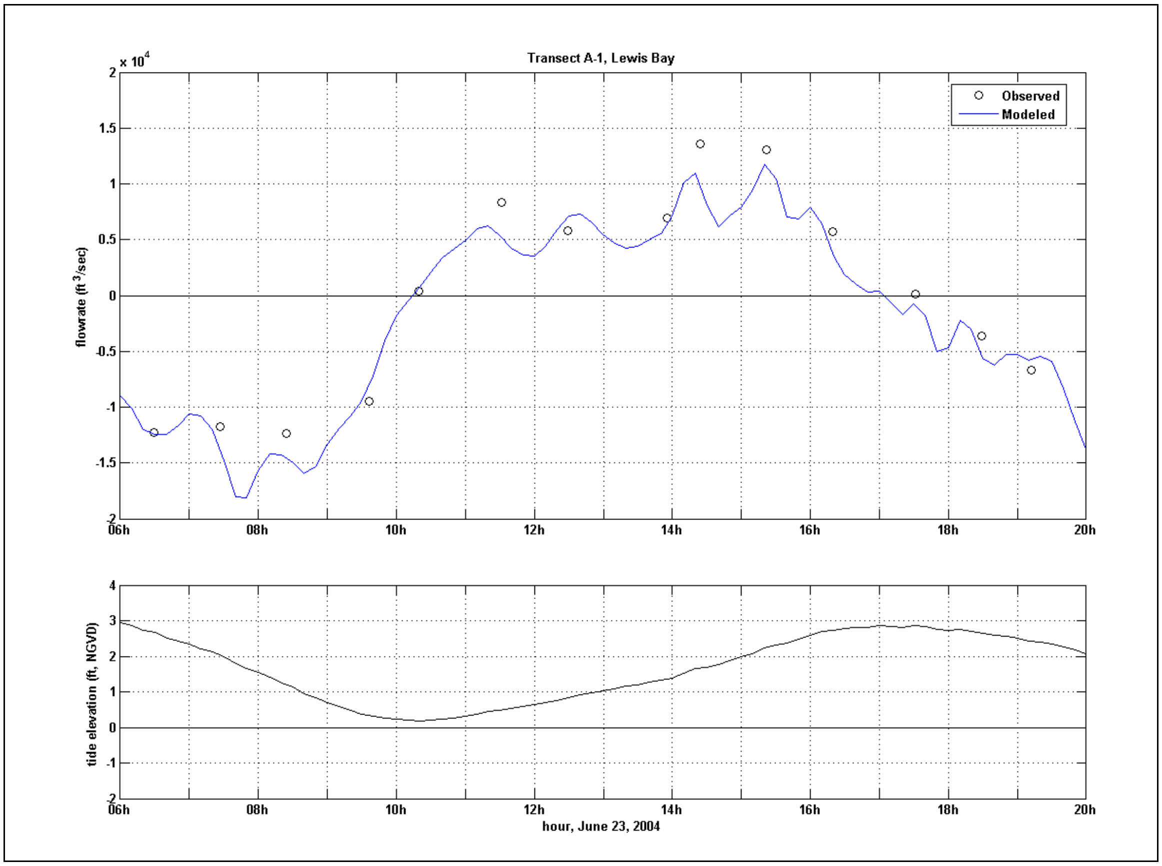


Figure V-28. Comparison of measured volume flow rates versus modeled flow rates (top plot) across the entrance to Lewis Bay (A-1), over a tidal cycle on June 23, 2004 (R^2 = 0.91). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Nantucket Sound.

V.3.5 Model Circulation Characteristics

The final calibrated and validated model serves as a useful tool for investigating the circulation characteristics of the Lewis Bay and Halls Creek estuarine systems. Using model inputs of bathymetry and tide data, current velocities and flow rates can be determined at any point in either 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.

V.3.5.1 Lewis Bay

From the model run of Lewis Bay, maximum ebb velocities at the inlet are larger than velocities during the flood portion of the tide. Maximum depth-averaged velocities in the model are approximately 2.9 feet/sec for ebbing tides, and 1.7 ft/sec for flooding tides. A close-up of the model output is presented in Figure V-29, which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow, for a single model time-step, at the portion of the tide where maximum ebb velocities occur at the inlet.

The hydraulic model shows that the culverts conveying tidal flows into Stewarts Creek and Snows Creek represent restrictions to the natural flow. The limited size of the culverts restricts the full hydraulic exchange of tidal waters between the main basin and embayment. The hydraulic efficiency of the existing culverts can be slightly improved by keep the openings and length of the culvert free of debris and any sediment buildup.

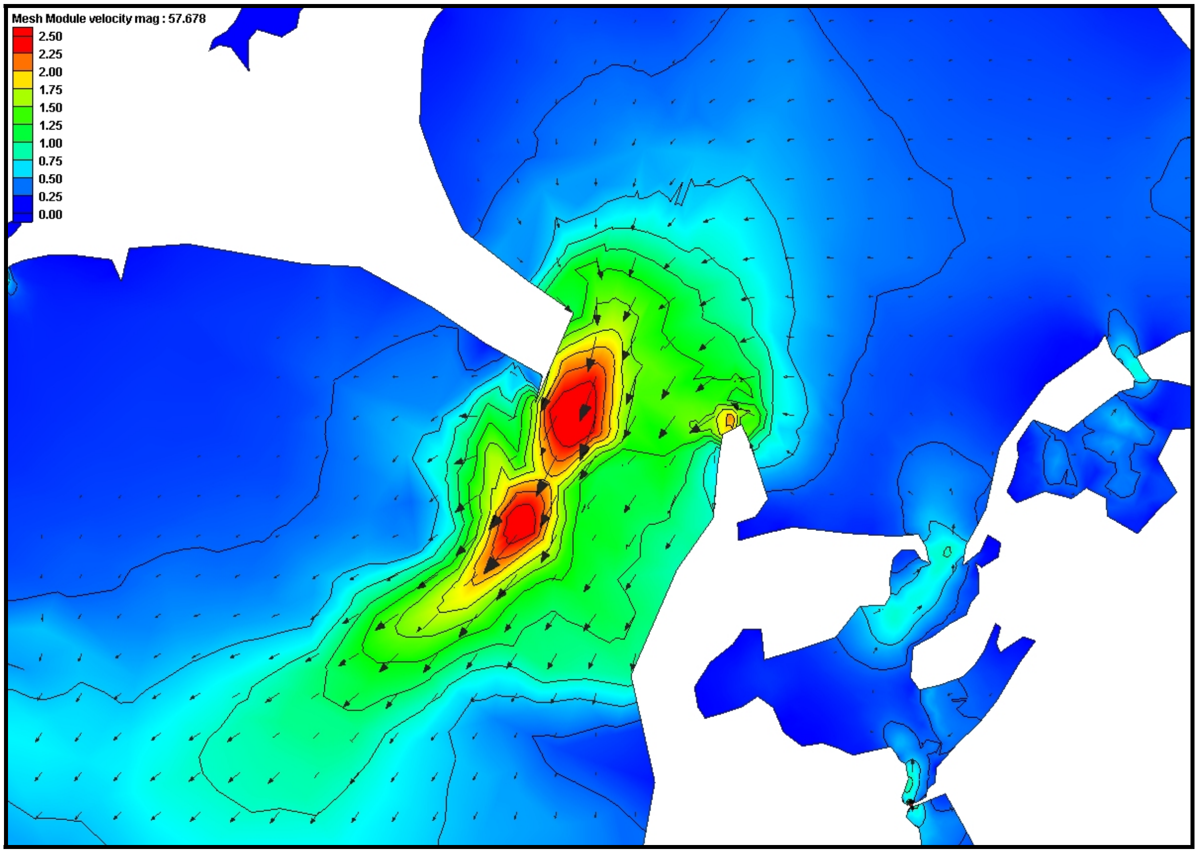


Figure V-29. Example of hydrodynamic model output in Lewis Bay for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

V.3.5.2 Halls Creek

From the model run of Halls Creek, maximum ebb velocities in the inlet channels are slightly larger than velocities during maximum flood. Maximum depth-averaged flood velocities in the model are approximately 2.7 feet/sec in the inlet channel, while maximum ebb velocities are about 3.1 feet/sec. Close-up views of model output are presented in Figure V-30 which shows contours of velocity magnitude along with velocity vectors that indicate flow direction for a single model time-step, at the portion of the tide where maximum ebb velocities.

In addition to depth-averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs at the two system inlets is seen in the plot of flow rates in Figure V-31. Maximum flow rates occur during flooding tides in this system. During spring tides, the maximum flood flow rates reach 1,300 ft^3/sec at the Creek inlet. Maximum ebb flow rates during spring tides are slightly smaller, at about 1,100 ft^3/sec. Minimum flood and ebb flows at the inlet during neap tides are both approximately 400 ft^3/sec.

Using the velocities computed in the model, an investigation of the flood or ebb dominance of different areas in the Halls Creek 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.

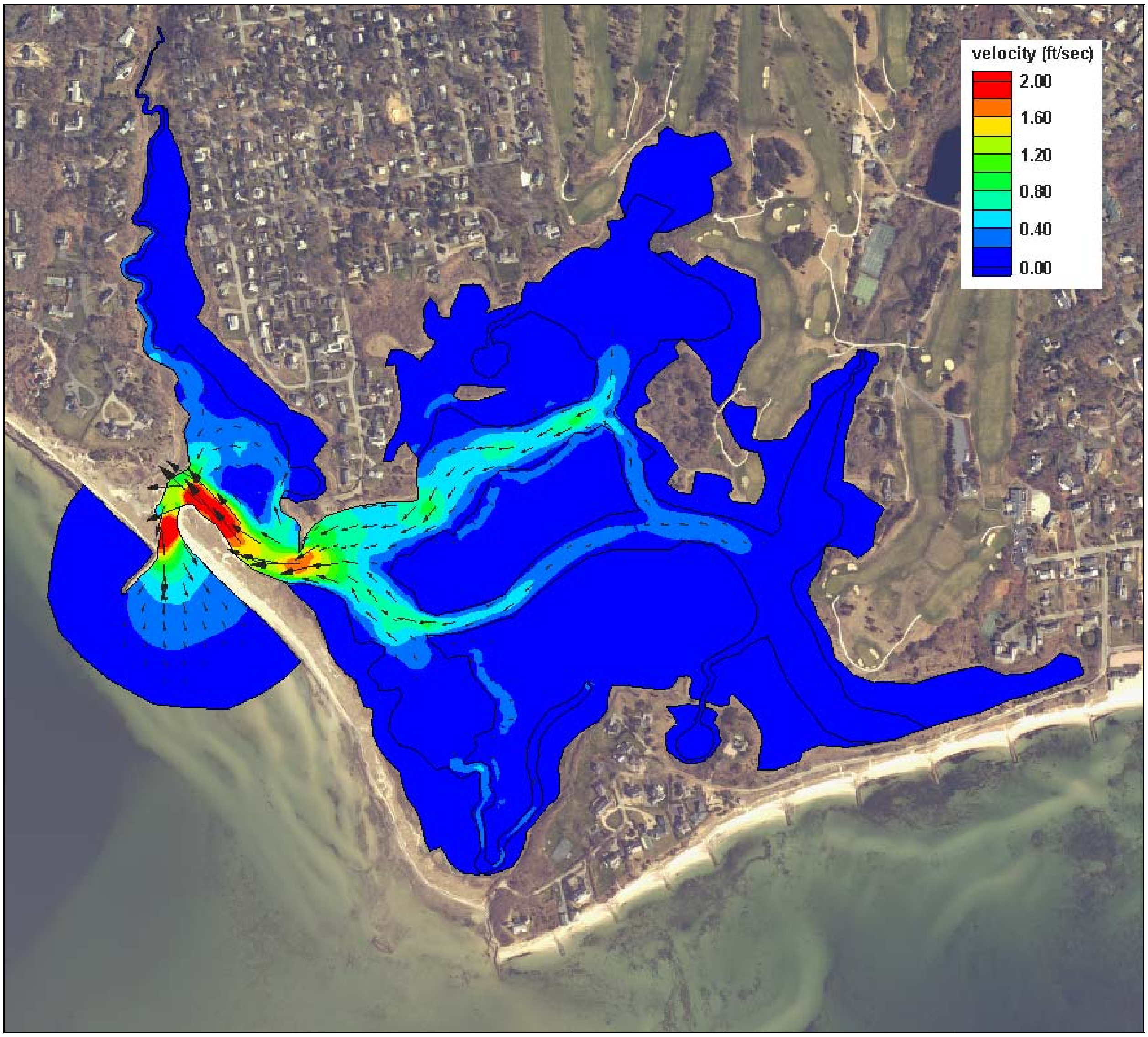


Figure V-30. Example of Halls Creek hydrodynamic model output for a single time step during an ebbing tide. Color contours indicate velocity magnitude, and vectors indicate the direction of flow. Material type boundaries are also shown as the solid black lines within the model domain.

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 time series are computed, similar to the tidal elevation constituents presented in Section V.3.3.4.

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<Φ<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<Φ<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-32.

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.

Three points were selected for this velocity analysis: 1) the inlet, 2) in the lower portion of the Creek at the same location of the tide gauge station inside the Creek and 3) in the upper Creek at a location 1,300 feet upstream from the tide gauge station.

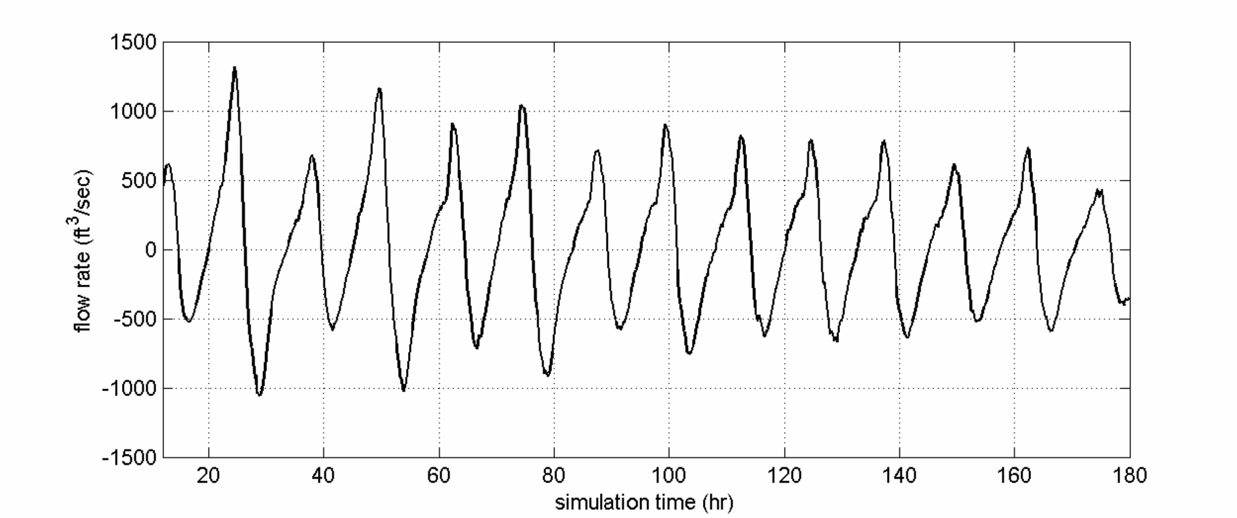


Figure V-31. Time variation of computed flow rates for Halls Creek. Plotted time period represents the seven-day period that includes the model calibration period. Positive flow indicated flooding tide, while negative flow indicates ebbing tide.

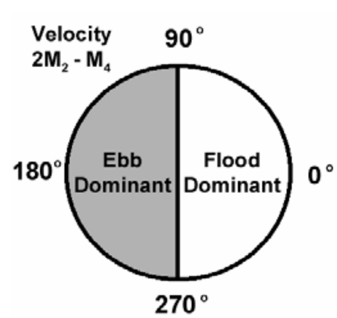


Figure V-32. Relative velocity phase relationship of M2 and M4 tidal velocity constituents and characteristic dominance, indicated on the unit circle. Relative phase is computed as the difference of two times the M_2 phase and the M_4 phase ($2M_2$-M_4). A relative phase of exactly 90 or 270 degrees indicates a symmetric tide, which is neither flood nor ebb dominant.

The results of this velocity analysis of the Halls Creek model output show that that, though the inlet area of the Creek is ebb dominant, upper portions of the system are indeed flood dominant, as is expected for a marsh. The computed values of $2M_2$-M_4 are presented in Table V-13. The first two locations, in the vicinity of the inlet, have a velocity constituent phase relationship that indicated that the tides in these areas are moderate ebb dominant. For the third location used in this analysis, which is farther into the system than the other two, the velocity constituent phase relationship indicates moderate flood dominance.

Table V-13. Halls Creek relative velocity phase differences of M_2 and M_4 tide constituents, determines using velocity records.

location	$2M_2$-M_4 relative phase (deg)	Characteristic dominance
Inlet	259.6	Moderate Ebb
Lower Halls Creek	113.3	Moderate Ebb
Upper Halls Creek	79.8	Moderate Flood

V.5 FLUSHING CHARACTERISTICS

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

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

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

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

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using the head of Hyannis Inner Harbor as an example, the **system residence time** is the average time required for water to migrate from the inner harbor, through Lewis Bay, and finally into Hyannis Harbor, where the **local residence time** is the average time required for water to migrate from the head of the inner harbor to out into Lewis Bay (not all the way to through inlet and out of the system). Local residence times for each sub-embayment are computed as:

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

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

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

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

The volume of the each sub-embayment, as well as their respective tidal prisms, were computed as cubic feet (Table V-14). Model divisions used to define the system sub-embayments for the Lewis Bay system include 1) the whole of system, 2) all of Lewis Bay (including all sub-embayments), 3) Hyannis Inner Harbor, 4) Uncle Roberts Cove, 5) Mill Creek, 6) Snows Creek, and 7) Stewarts Creek. For Halls Creek, the flushing calculation was performed on the whole system only.

The model computed total volume of each sub-embayment (using the divisions shown in Figure V-12 and V-14, for Lewis Bay and Halls Creek, respectively), at every time step, and this output was used to calculate mean sub-embayment volume and average tide prism. Since the period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

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

The whole of Hyannis Harbor/Lewis Bay system has a low residence time (1.1 days) showing that the system has good flushing conditions. This is true of all the local residence times for the system. The only embayment with moderately high local residence time (3.7 days) is Snows Creek. The flow into and out of Snows Creek is restricted by the narrow channel and the culvert under Ocean Street. The longer residence times suggest that the water quality within the Snow Creek is highly sensitive to the combined nutrient load input from the system watersheds, benthic sediments and direct atmospheric deposition. The system residence time for Snows Creek does not provide a good indication of the water quality since the variation in basin volumes from Snows Creek to the system volume is considerable. The result is a very long system residence time which should not be considered an accurate characterization of the conditions occurring in the creek.

The computed flushing rate for the Halls Creek system show that as a whole, the system flushes very well, as is typical of marsh systems. A flushing time of 0.4 days for the entire estuary shows that on average, water is resident in the system less than one day.

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

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

Table V-14. Embayment mean volumes and average tidal prism of the Lewis Bay and Halls Creek system during the simulation periods.		
Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Lewis Bay an Hyannis Harbor		
Entire System	1,368,016,852	645,052,581
Lewis Bay with sub-embayments	452,424,905	284,845,281
Hyannis Inner Harbor	23,711,223	11,275,304
Uncle Roberts Cove	18,052,002	18,972,946
Mill Creek	8,528,184	14,355,607
Snows Creek	3,017,376	421,485
Stewarts Creek	2,887,656	786,042
Halls Creek		
Halls Creek	6,969,000	9,203,000

Table V-15. Computed System and Local residence times for sub-embayments of the Lewis Bay estuary and Halls Creek marsh.		
Embayment	System Residence Time (days)	Local Residence Time (days)
Lewis Bay an Hyannis Harbor		
Entire System	1.1	1.1
Lewis Bay with sub-embayments	0.8	0.8
Hyannis Inner Harbor	2.1	1.1
Uncle Roberts Cove	1.2	0.5
Mill Creek	1.6	0.3
Snows Creek	558.2	3.7
Stewarts Creek	---	1.9
Halls Creek		
Halls Creek	0.4	0.4

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 both the Lewis Bay and Halls Creeks systems. 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-2V 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. For Lewis Bay, the period of hydrodynamic output for the water quality model calibration was an 11-tidal cycle period in June 2004. For Halls Creek, the period of hydrodynamic output for the water quality model calibration was the 6 day period beginning July 3, 2004 1900 EST. Each modeled scenario executed for both systems (e.g., present conditions, build-out) required that each model be run for a 28-day spin-up period, to allow the model had reached 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 Lewis Bay and Halls Creek systems, 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 grids.

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 and VI-2 for Lewis Bay and Halls Creek, respectively. Station locations are indicated in Figure VI-1 and VI-1 for the two separate systems. 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 an analysis. Six years of data (collected between 2001 and 2006) were available for stations monitored by SMAST in the Lewis Bay and Halls Creek systems.

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 Lewis Bay and Halls Creek estuarine systems.

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 both estuarine systems in this analysis. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod embayments, including systems in Falmouth (Ramsey *et al*., 2000); Mashpee, MA (Howes *et al*., 2004) and Chatham, MA (Howes *et al*., 2003).

The overall approach involves modeling total nitrogen as a non-conservative constituent, where bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. This modeling represents summertime conditions, when algal growth is at its maximum. Total nitrogen modeling is based upon various data collection efforts and analyses presented in previous sections of this report. Nitrogen loading information was derived from the Cape Cod Commission watershed loading analysis (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 each system.

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

Table VI-1. Towns of Barnstable and Yarmouth water quality monitoring data, and modeled Nitrogen concentrations for the Lewis Bay 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	Hyannis Inner Harbor	Hyannis Inner Harbor	Hyannis Inner Harbor	Snows Creek	Lewis Bay	Lewis Bay	Stewarts Creek	Lewis Bay	Lewis Bay	Lewis Bay	Uncle Roberts Cove	Mill Creek	Mill Creek
Monitoring station	BH-1	BH-2	BH-3	BH-4	BH-5	BH-6	BH-7	BHY-1	BHY-2	BHY-3	BHY-4	MC-1	MC-2
2001 mean	0.422	0.327	0.351	1.422	0.298	0.308	--	0.270	0.329	0.333	--	--	--
2002 mean	0.634	0.535	0.483	1.459	0.399	0.415	1.257	0.358	0.420	0.369	--	0.469	0.476
2003 mean	0.676	0.494	0.491	1.873	0.420	0.349	1.411	0.351	0.420	0.405	--	0.555	0.510
2004 mean	0.580	0.492	0.368	1.295	0.372	0.353	1.023	0.445	0.496	0.424	0.469	0.594	0.523
2005 mean	0.526	0.413	0.400	1.450	0.325	0.349	1.016	0.326	0.373	0.371	0.364	0.500	0.463
2006 mean	0.585	0.468	0.416	1.917	0.344	0.421	1.606	0.435	0.476	0.461	0.391	0.749	0.638
mean	0.599	0.474	0.433	1.565	0.374	0.373	1.245	0.374	0.430	0.395	0.410	0.562	0.516
s.d. all data	0.140	0.100	0.097	0.442	0.089	0.095	0.399	0.115	0.111	0.095	0.091	0.162	0.128
N	55	58	55	33	57	61	31	63	59	60	8	27	26
model min	0.561	0.501	0.420	0.395	0.376	0.336	0.923	0.361	0.393	0.404	0.421	0.466	0.419
model max	0.585	0.537	0.488	2.022	0.401	0.399	1.643	0.406	0.475	0.412	0.442	0.665	0.608
model average	0.574	0.518	0.445	1.638	0.388	0.369	1.377	0.385	0.415	0.408	0.432	0.532	0.474

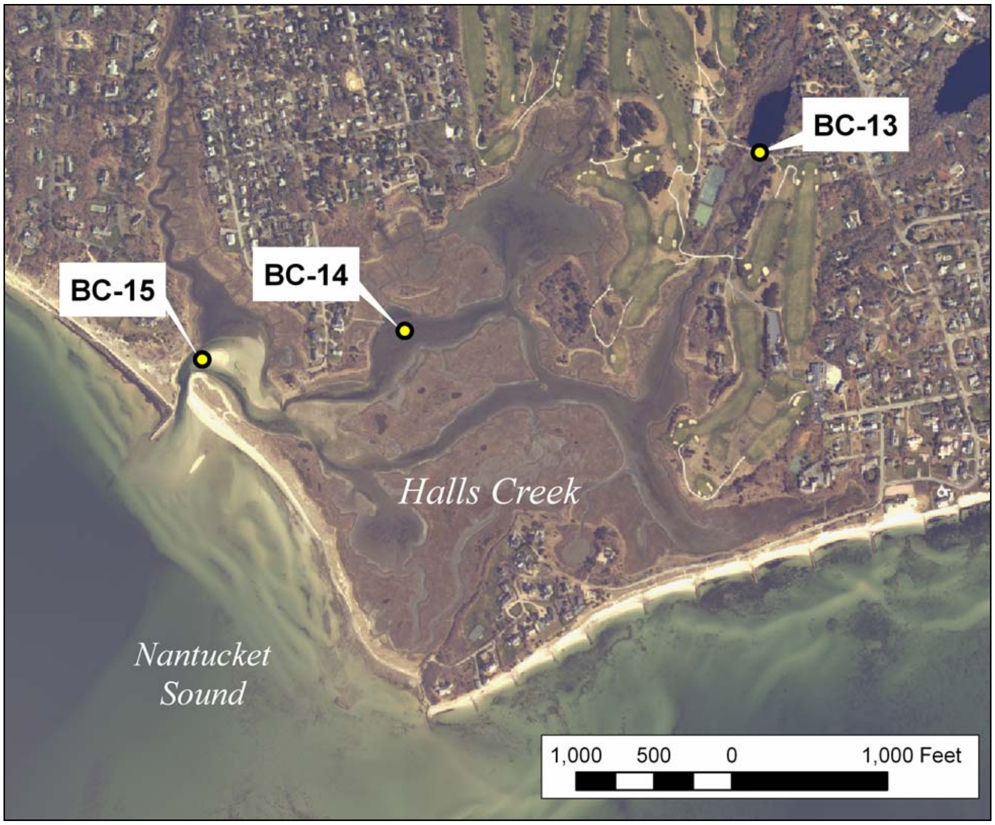


Figure VI-2. Estuarine water quality monitoring station locations in the Halls Creek estuary system. Station labels correspond to those provided in Table VI-2.

Table VI-2. Measured data and modeled nitrogen concentrations for the Halls Creek estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average all samples. Halls Creek data represented in this table were collected in the summers of 2001 through 2006.

Sub-Embayment	monitoring station	data mean	s.d. all data	N	model min	model max	model average	model target
Halls Creek Stream	BC-13	1.213	0.410	24	0.703	1.863	1.171	1.213
Halls Creek - middle	BC-14	0.454	0.083	26	0.302	0.685	0.433	0.454
Halls Creek - inlet	BC-15	0.431	0.083	28	0.293	0.568	0.349	0.431
Nantucket Sound	NTKS	0.294	0.062	4	-	-	-	0.294

VI.2.1 Model Formulation

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

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

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

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

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

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 Lewis Bay and Halls Creek systems was used for the water quality constituent modeling portion of this study.

Based on measured flow rates from SMAST and groundwater recharge rates from the USGS, the hydrodynamic model was set-up to include the latest estimate of surface water flows from Chase Brook, Mill Pond, Snows Creek, Stewarts Creek, and Hospital Creek/Hyannis Inner Harbor Creek along with ground water flowing into the system from watersheds. The Chase Brook has a measure flow rate of 1.33 ft^3/sec (3,255 m^3/day), Mill Pond has a measure flow rate of 6.40 ft^3/sec (15,655 m^3/day), Snows Creek has a measure flow rate of 2.17 ft^3/sec (5,298 m^3/day), Stewarts Creek has a measure flow rate of 5.71 ft^3/sec (13,966 m^3/day), and Hospital Creek/Hyannis Inner Harbor Creek has a measure flow rate of 0.54 ft^3/sec (1,318 m^3/day). The overall groundwater flow rate into the system is 6.38 ft^3/sec (15,614 m^3/day) distributed amongst the watersheds.

For Halls Creek, the hydrodynamic model was set-up to include the latest estimates of flows from the surface freshwater input to the marsh from Halls Creek stream (0.484 ft^3/sec), based on stream gauge measurements performed by SMAST. The groundwater inputs to the system are an additional 3.20 ft^3/sec (7,820 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 7 tidal-day (174 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for both the Lewis Bay and Halls Creek systems.

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, 3) summer benthic regeneration, and 4) point source input developed from measurements of from Chase Brook, Mill Pond, and Hospital Creek/Hyannis Inner Harbor Creek for Lewis Bay, and Halls Creek stream for Halls Creek. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed direct atmospheric deposition load for Uncle Roberts Cove was evenly distributed at grid cells that formed the perimeter of 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 are given in Table VI-3 for Lewis Bay,and Figure VI-4 for Halls Creek. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For present conditions, some sub-embayments have almost twice the loading rate from benthic regeneration as from watershed loads. For other sub-embayments, the benthic flux is relatively low or negative indicating a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in Nantucket Sound was set at 0.30 mg/L, based on SMAST data from the Sound. The open boundary total nitrogen concentration represents long-term average summer concentrations found within Nantucket Sound.

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 V-12 for Lewis Bay and V-14 for Halls Creek. 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 Lewis Bay and Halls Creek 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-5. 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. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay 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)
Lewis Bay	30.855	13.507	25.999
Uncle Roberts Cove	0.540	0.759	12.771
Mill Creek	15.964	0.627	-15.355
Hyannis Inner Harbor	12.153	0.633	18.660
Snows Creek	15.115	-	-4.533
Stewarts Creek	38.992	0.236	-9.750
Surface Water Sources			
Chase Brook	3.345	-	-
Mill Pond	15.038	-	-
Hospital Creek/Hyannis Inner	1.907	-	-

Table VI-4. Sub-embayment and surface water loads used for total nitrogen modeling of the Halls Creek system, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions** for the listed sub-embayments.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Halls Creek	21.534	0.630	5.252
Halls Creek Stream (freshwater)	1.597	-	-
System Total	23.132	0.630	5.252

Table VI-5. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for the Lewis Bay and Halls Creek systems.	
Embayment Division	E m^2/sec
Lewis Bay and Hyannis Harbor	
Hyannis Harbor	10.0
Lewis Bay	8.0
Uncle Roberts Cove	9.0
Uncle Roberts Cove (marsh)	1.0
Snows Creek	6.0
Pine Island Creek	3.0
Mill Creek	4.0
Mill Creek (marsh)	1.0
Mill Creek (creek on eastern edge)	10.0
Mill Creek (culvert)	4.0
Hyannis Inner Harbor	3.0
Snows Creek Inlet	1.0
Sweetheart Creek	3.0
Stewarts Creek	6.0
Stewarts Creek (culvert)	6.0
Halls Creek	
Inlet – Nantucket Sound	0.45
Halls Creek - east branch	0.45
Halls Creek - west branch	0.45
second order marsh channels	0.45
Marsh Plain	0.45

Comparisons between model output and measured nitrogen concentrations are shown in plots presented in Figures VI-3 and VI-4 for Lewis Bay and Halls Creek, respectively. 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 Pond-Watcher 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.

Also presented in these figures are unity plot comparisons of measured data verses modeled target values for the system. The model of the Lewis Bay system shows good agreement with the measured data, with RMS error of 0.11 mg/L and an R^2 correlation coefficient of 0.91. The Halls Creek Model demonstrates similar skillful representation of the measured data, with a R^2 value of 0.99 and an RMS error of 0.03 mg/L.

Contour plots of calibrated model output are shown in Figure VI-5 for the Lewis Bay system and Figure V-6 for Halls Creek. 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.

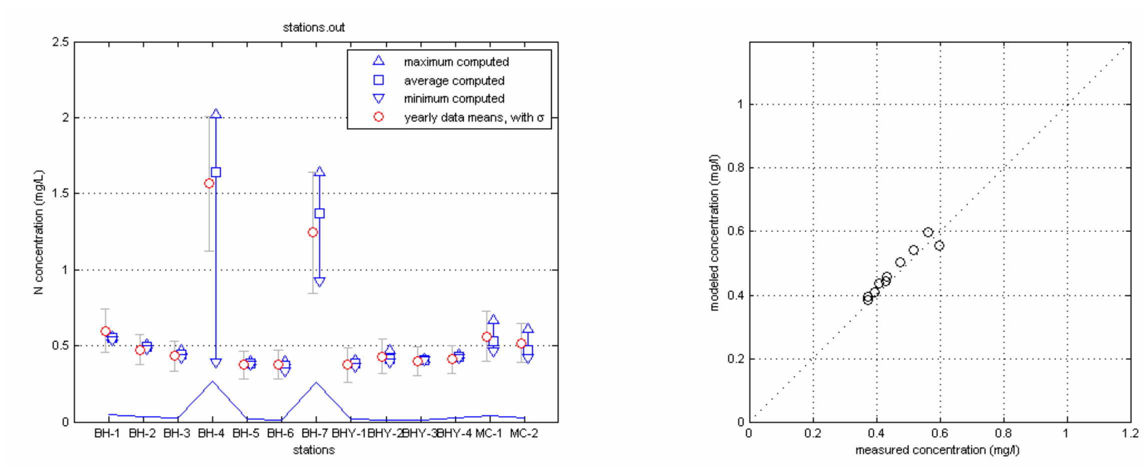


Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Lewis Bay estuary system. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed 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. Computed correlation (R^2) and error (rms) for each model are also presented.

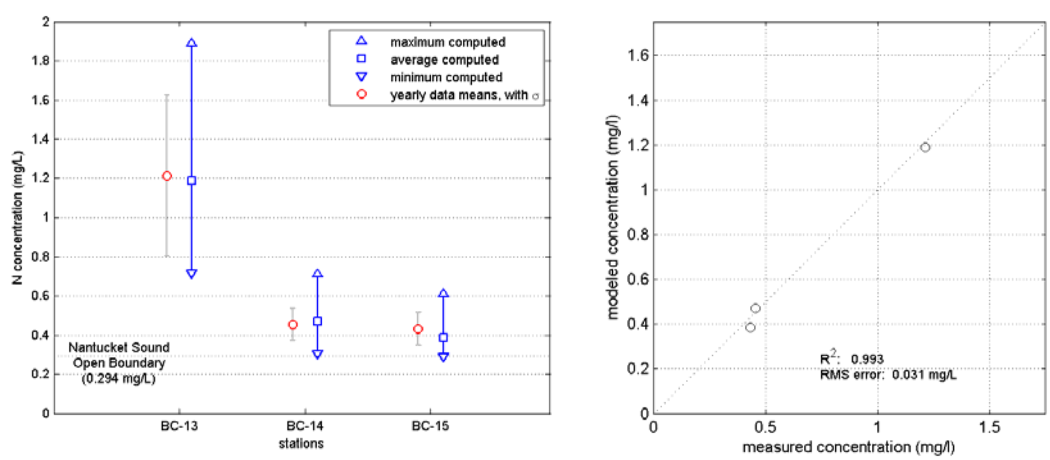


Figure VI-4. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Halls Creek. Plots are interpreted similarly as those for Lewis Bay in Figure VI-3.

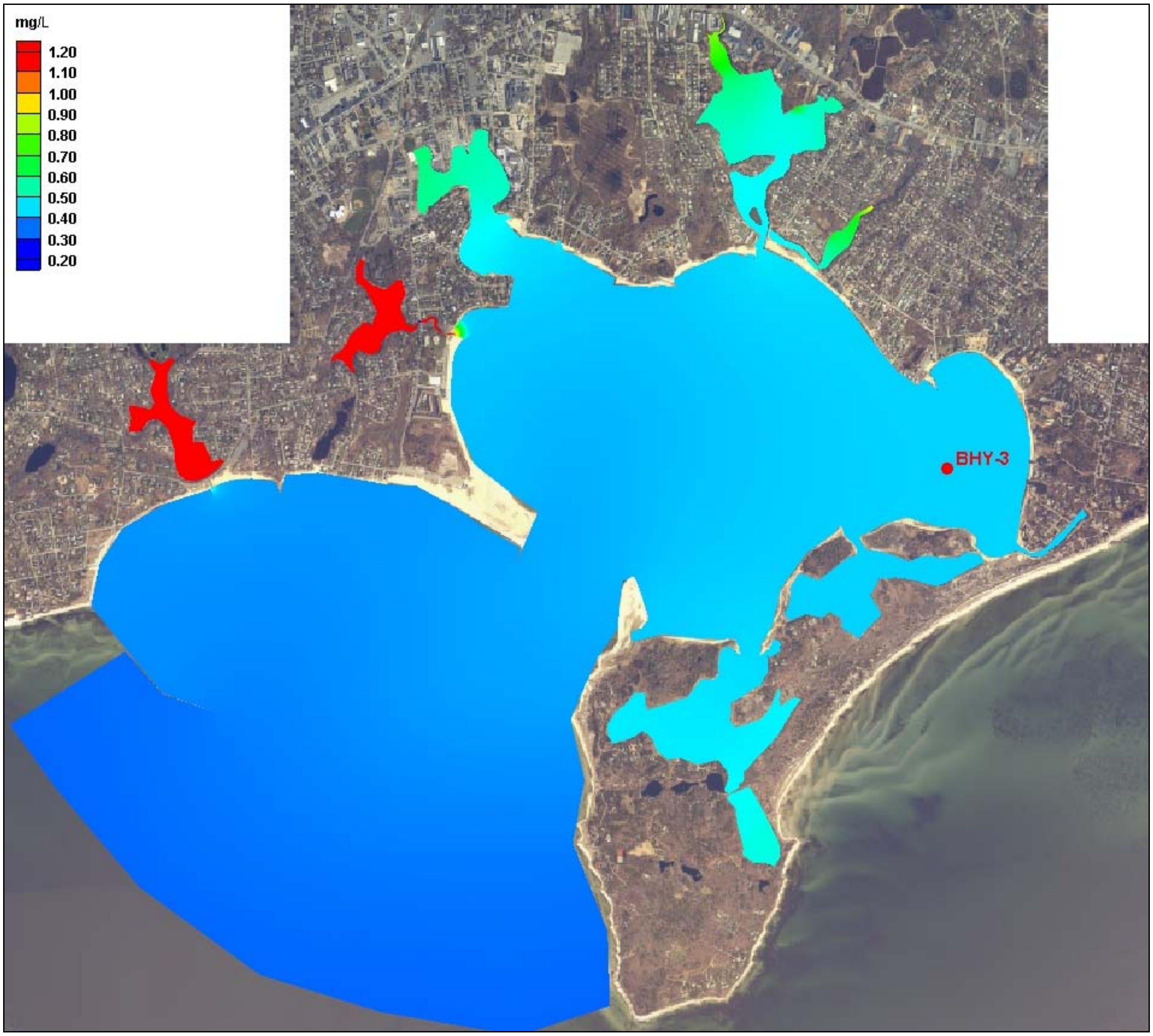


Figure VI-5 Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for the Lewis Bay system. The approximate location of the sentinel threshold station for the Lewis Bay system (BHY-3) is shown.

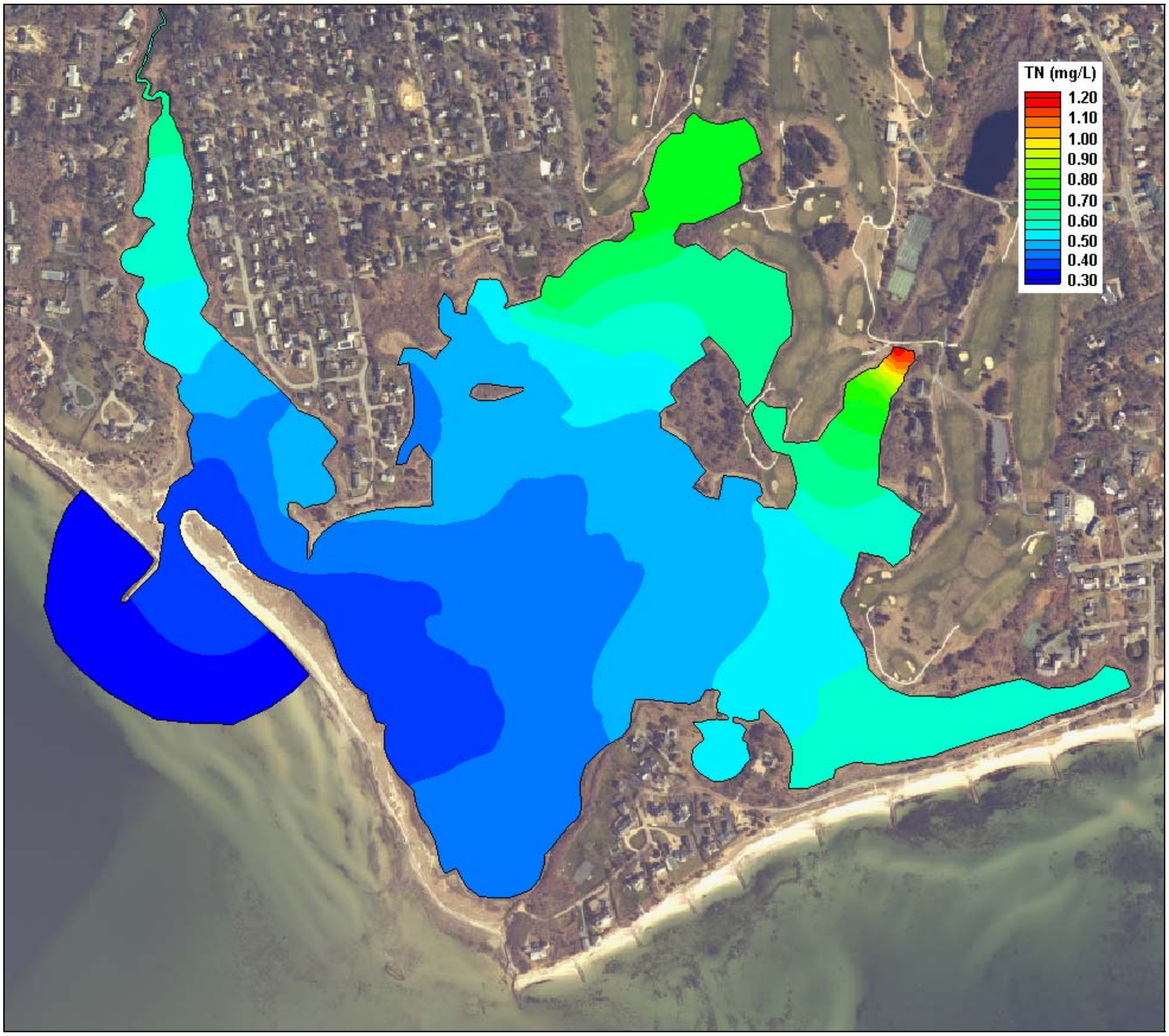


Figure VI-6. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Halls Creek system.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for both the Lewis Bay and Halls Creek systems 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 30.8 ppt. For groundwater inputs salinities were set at 0 ppt. Groundwater input used for the model was a total of 6.38 ft^3/sec (15,614 m^3/day) for Lewis Bay and 3.20 ft^3/sec (7,820 m^3/day) for Halls Creek. Groundwater flows were distributed evenly in each model through the use of 1-D element input points positioned along each model's land boundary.

Comparisons of modeled and measured salinities are presented in Figure VI-7 and VI-8 for Lewis Bay and Halls Creek, respectively, with contour plots of model output shown in Figure

VI-9 and VI-10. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the modesl skillfully represents salinity gradients in both systems.

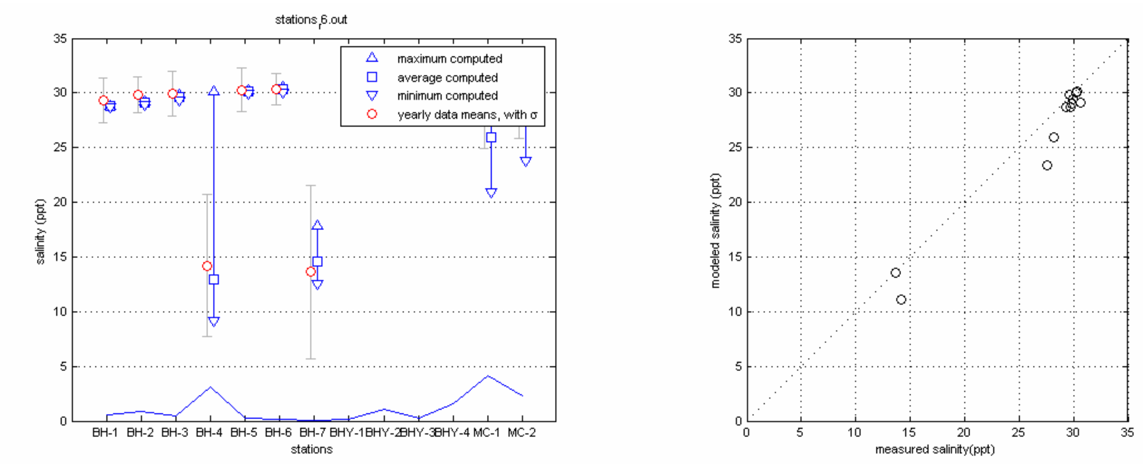


Figure VI-7. Comparison of measured and calibrated model output at stations in the Lewis Bay system. For the left plot, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle 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 plot to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

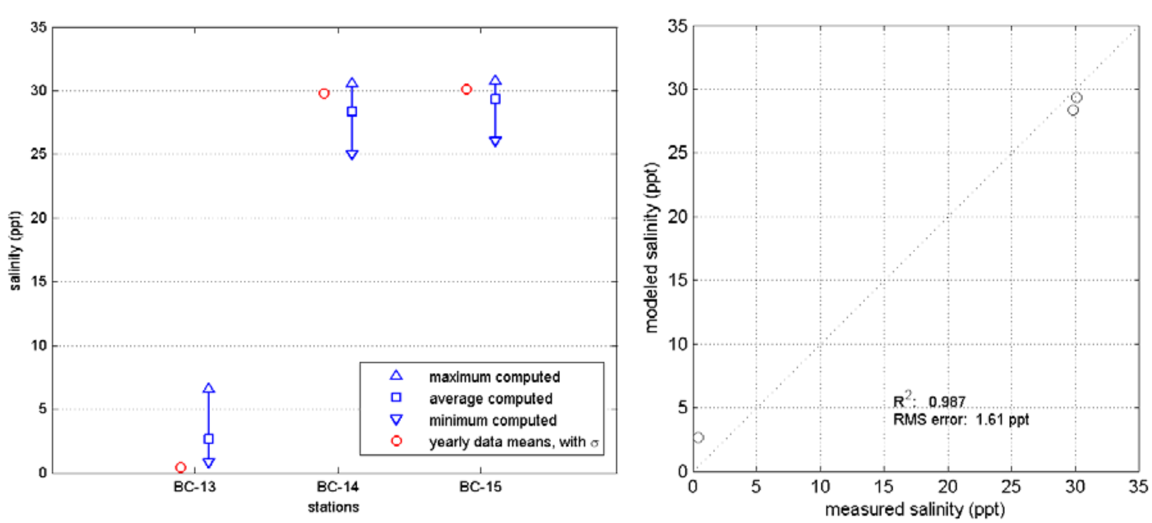


Figure VI-8. Comparison of measured salinity and calibrated model output at stations in Halls Creek. Plots are interpreted similarly as those for Lewis Bay in Figure VI-7.

For the Lewis Bay model, the RMS error of the models is 1.14 ppt, and correlation coefficient is 0.91. For Halls Creek, the RMS error of the model is less than 1.7 ppt, and the R^2 correlation coefficient of the model and measured salinity data is 0.987 The salinity verifications provide a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical systems.

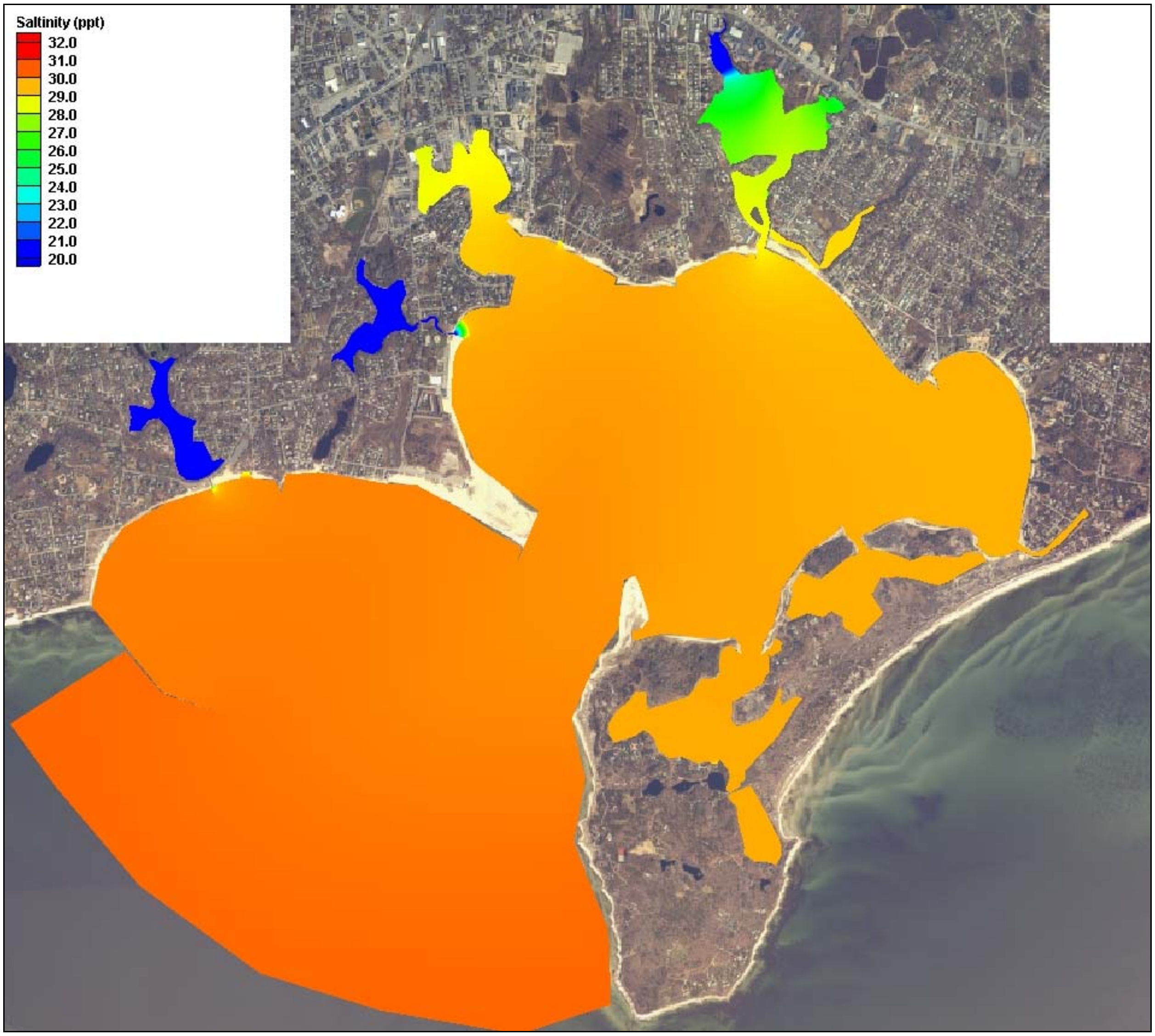


Figure VI-9. Contour plots of modeled salinity (ppt) in the Lewis Bay system.

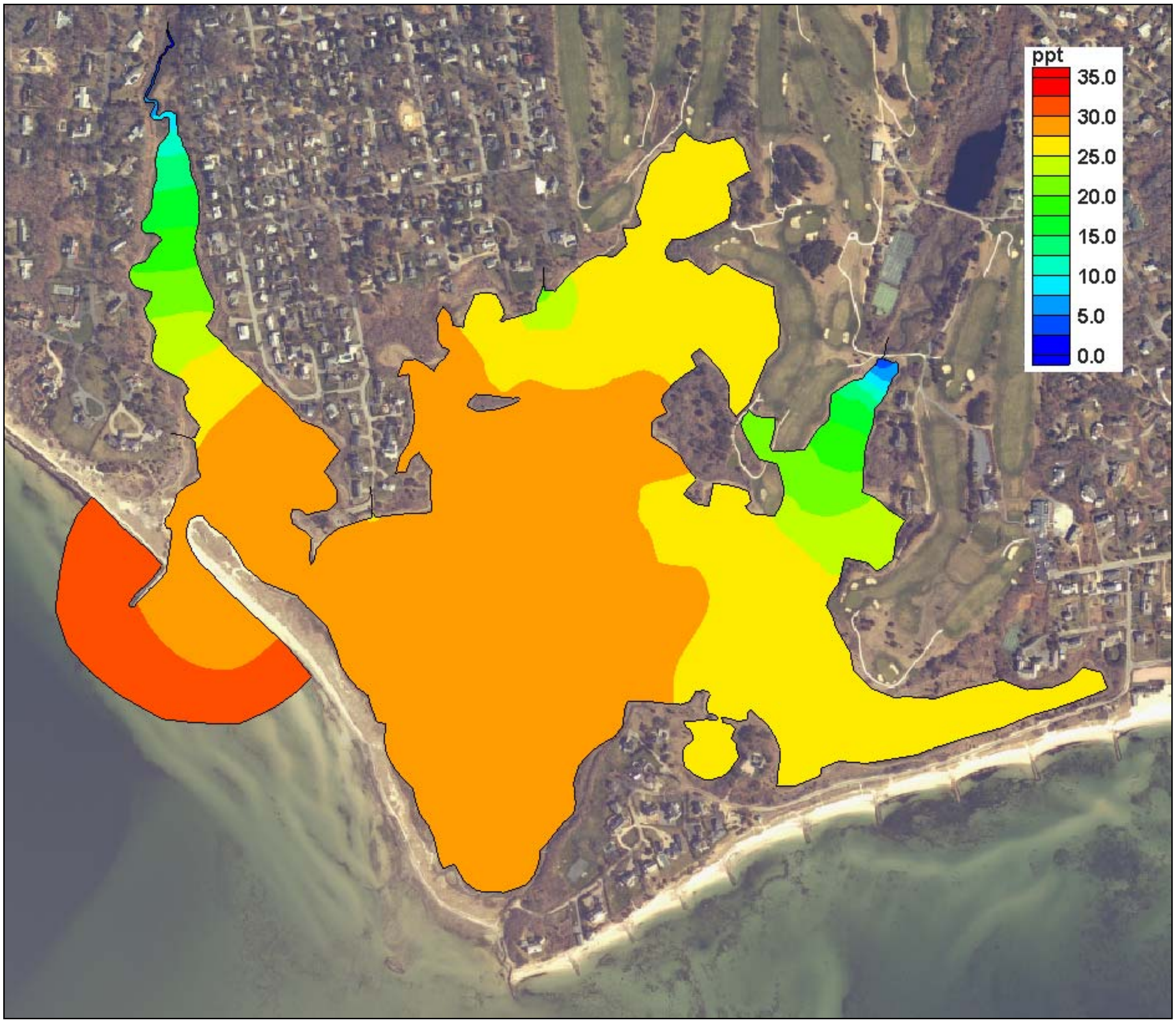


Figure VI-10. Contour Plot of modeled salinity (ppt) in the Halls Creek system.

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-6 For Lewi s Bay and VI-7 for Halls Creek. 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.

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be more than a 12% increase in watershed nitrogen load to the Lewis Bay and a 17% increase for Halls Creek as a result of potential future development.

Other watershed areas would experience larger load increases, for example the loads to Mill Creek would increase 38% from the present day loading levels.

For the no load scenarios, a majority of the load entering the watersheds of the two separate systems is removed; therefore, the load is generally lower than existing conditions by over 90% overall and 95% in most areas.

Table VI-6. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Lewis Bay 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
Lewis Bay	30.855	34.562	+12.0%	0.564	-98.2%
Uncle Roberts Cove	0.540	0.715	+32.5%	0.096	-82.2%
Mill Creek	15.964	22.066	+38.2%	0.405	-97.5%
Hyannis Inner Harbor	12.153	14.934	+22.9%	0.485	-96.0%
Snows Creek	15.115	21.532	+42.5%	0.293	-98.1%
Stewarts Creek	38.992	53.959	+38.4%	0.485	-98.8%
Surface Water Sources					
Chase Brook	3.345	4.066	+21.5%	0.140	-95.8%
Mill Pond	15.038	23.342	+55.2%	1.033	-93.1%
Hospital Creek/Hyannis Inner	1.907	1.956	+2.6%	0.060	-96.8%

Table VI-7. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Halls Creek 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
Halls Creek	21.534	25.419	+18.0%	0.844	-96.1%
Halls Creek Stream (fresh)	1.597	1.649	+3.3%	0.060	-96.2%
System Total	23.132	27.068	+17.0%	0.904	-96.1%

VI.2.6.1 Build-Out

For the build-out scenario, a breakdown of the total nitrogen load entering the Lewis Bay system sub-embayments is shown in Table VI-8, and for Halls Creek the build-out load are shown in Table VI-9. 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-8. **Build-out** sub-embayment and surface water loads used for total nitrogen modeling of the Lewis Bay 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)
Lewis Bay	34.562	13.507	28.153
Uncle Roberts Cove	0.715	0.759	14.431
Mill Creek	22.068	0.627	-1.927
Hyannis Inner Harbor	14.934	0.633	13.767
Snows Creek	21.532	-	-6.458
Stewarts Creek	53.959	0.236	-13.489
Surface Water Sources			
Chase Brook	4.066	-	-
Mill Pond	23.342	-	-
Hospital Creek/Hyannis Inner	1.956	-	-

Table VI-9. **Build-out** sub-embayment and surface water loads used for total nitrogen modeling of the Halls Creek 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)
Halls Creek	25.419	0.630	5.679
Halls Creek Stream (freshwater)	1.649	-	-
System Total	27.068	0.630	5.679

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of the Lewis Bay and Halls Creek were run to determine nitrogen concentrations within across the sub-embayments of these systems (Table VI-10 for Lewis Bay and Table VI-11 for Halls Creek). Total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios.

For Lewis Bay, total N concentrations increased the most in the upper portion of the system, with the largest change occurring in Snows Creek (34%) and the least change occurring in Lewis Bay (3%). Color contours of model output for the build-out scenario for Lewis Bay 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-11, which allows direct comparison of nitrogen concentrations between loading scenarios.

For Halls Creek, total N concentrations increased the most in the mid creek monitoring station (BC-14), with an increase of 5.4%. The least change occurs in the creek inlet (3.4% BC-15) to Nantucket Sound (3.4% BC-15). Color contours of model output for the build-out scenario of Halls Creek are present in Figure VI-12.

Table VI-10. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Lewis Bay system. Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.591**	**+7.6%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.529**	**+6.7%**
Hyannis Inner Harbor	BH-3	0.440	0.464	+5.5%
Snows Creek	BH-4	1.638	2.186	+33.5%
Lewis Bay	BH-5	0.387	0.403	+4.1%
Lewis Bay	BH-6	0.368	0.380	+3.3%
Stewarts Creek	BH-7	1.374	1.772	+29.0%
Lewis Bay	BHY-1	0.384	0.399	+4.0%
Lewis Bay	BHY-2	0.414	0.440	+6.4%
Lewis Bay	**BHY-3**	**0.407**	**0.428**	**+5.1%**
Uncle Roberts Cove	BHY-4	0.431	0.453	+5.3%
Mill Creek	**MC-1**	**0.531**	**0.632**	**+19.0%**
Mill Creek	MC-2	0.473	0.529	+11.8%

Table VI-11. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Halls Creek system.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Halls Creek - stream	BC-13	1.189	1.239	+4.3%
Halls Creek - mid	BC-14	0.469	0.494	+5.4%
Halls Creek - inlet	BC-15	0.385	0.398	+3.4%

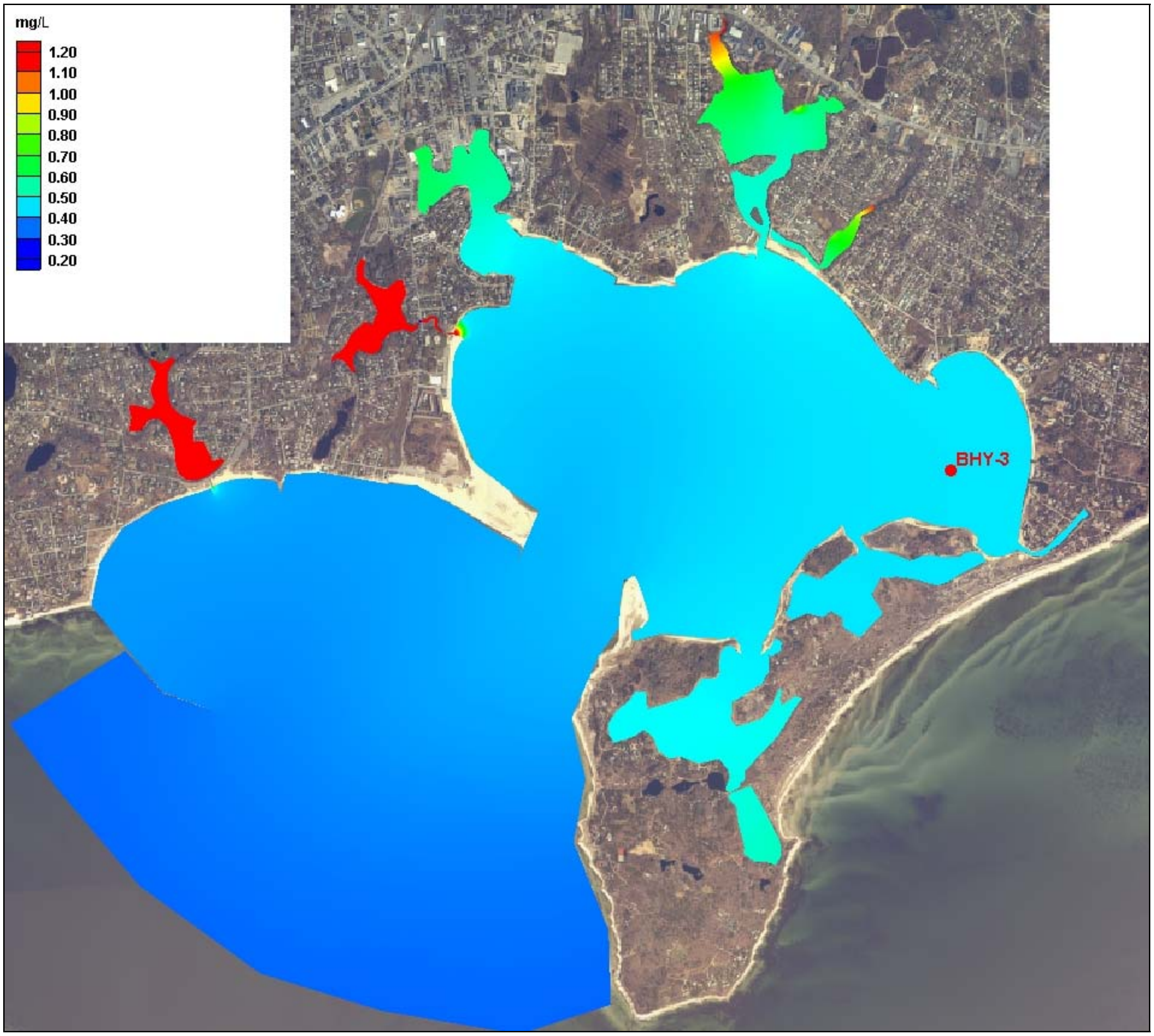


Figure VI-11. Contour plots of modeled total nitrogen concentrations (mg/L) in the Lewis Bay system, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold station for the Lewis Bay system (BHY-3) is shown.

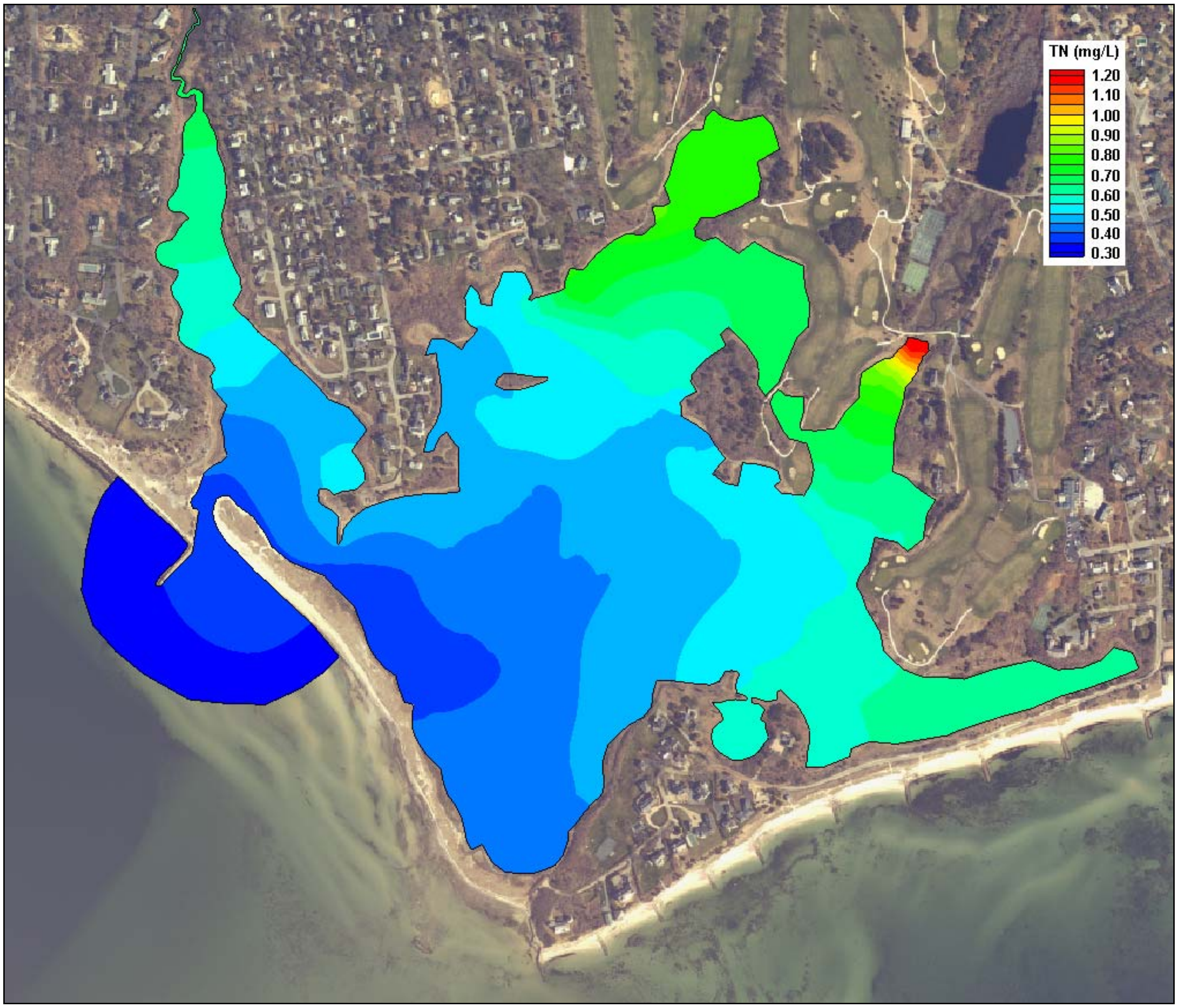


Figure VI-12 Contour plot of modeled total nitrogen concentrations (mg/L) in the Halls Creek system, for projected build-out loading conditions.

VI.2.6.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering each system sub-embayment for the no anthropogenic load ("no load") scenario is shown in Table VI-12 for Lewis Bay and Table VI-13 for Halls Creek. 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-12. "No anthropogenic loading" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Lewis Bay 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)
Lewis Bay	0.564	13.507	20.418
Uncle Roberts Cove	0.096	0.759	8.184
Mill Creek	0.405	0.627	-0.653
Hyannis Inner Harbor	0.485	0.633	6.408
Snows Creek	0.293	-	-0.089
Stewarts Creek	0.485	0.236	-0.125
Surface Water Sources			
Chase Brook	0.140	-	-
Mill Pond	1.033	-	-
Hospital Creek/Hyannis Inner	0.060	-	-

Table VI-13. "**No anthropogenic loading**" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Halls Creek 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)
Halls Creek	0.844	0.630	2.921
Halls Creek Stream (freshwater)	0.060	-	-
System Total	0.904	0.630	2.921

Similar to the build-out scenario, 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., Nantucket Sound) remained identical to the existing conditions modeling scenarios.

In Lewis Bay, the relative change in total nitrogen concentrations resulting from "no load" was significant as shown in Table VI-14, with reductions ranging from 10% occurring in Lewis Bay to greater than 70% within Snows and Stewarts Creek. Results for each system are shown pictorially in Figure VI-13.

From the model of Halls Creek, the change in total nitrogen concentrations was also large as shown in Table VI-15, with reductions greater than 59% occurring the upper portions of the system(at BC-13). Results for the system are shown pictorially in Figure VI-14.

Table VI-14. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the Lewis Bay system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.382**	**-30.4%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.365**	**-26.4%**
Hyannis Inner Harbor	BH-3	0.440	0.348	-20.8%
Snows Creek	BH-4	1.638	0.355	-78.4%
Lewis Bay	BH-5	0.387	0.332	-14.0%
Lewis Bay	BH-6	0.368	0.328	-10.8%
Stewarts Creek	BH-7	1.374	0.341	-75.2%
Lewis Bay	BHY-1	0.384	0.333	-13.3%
Lewis Bay	BHY-2	0.414	0.335	-19.2%
Lewis Bay	**BHY-3**	**0.407**	**0.338**	**-17.1%**
Uncle Roberts Cove	BHY-4	0.431	0.358	-17.0%
Mill Creek	**MC-1**	**0.531**	**0.308**	**-42.1%**
Mill Creek	MC-2	0.473	0.323	-31.7%

Table VI-15. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the Halls Creek system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The sentinel threshold station is in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no load (mg/L)	% change
Halls Creek - stream	BC-13	1.189	0.480	-59.6%
Halls Creek - mid	BC-14	0.469	0.329	-29.7%
Halls Creek - inlet	BC-15	0.385	0.313	-18.8%

Figure VI-13 Contour plots of modeled total nitrogen concentrations (mg/L) in the Lewis Bay system, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold station for the Lewis Bay system (BHY-3) is shown.

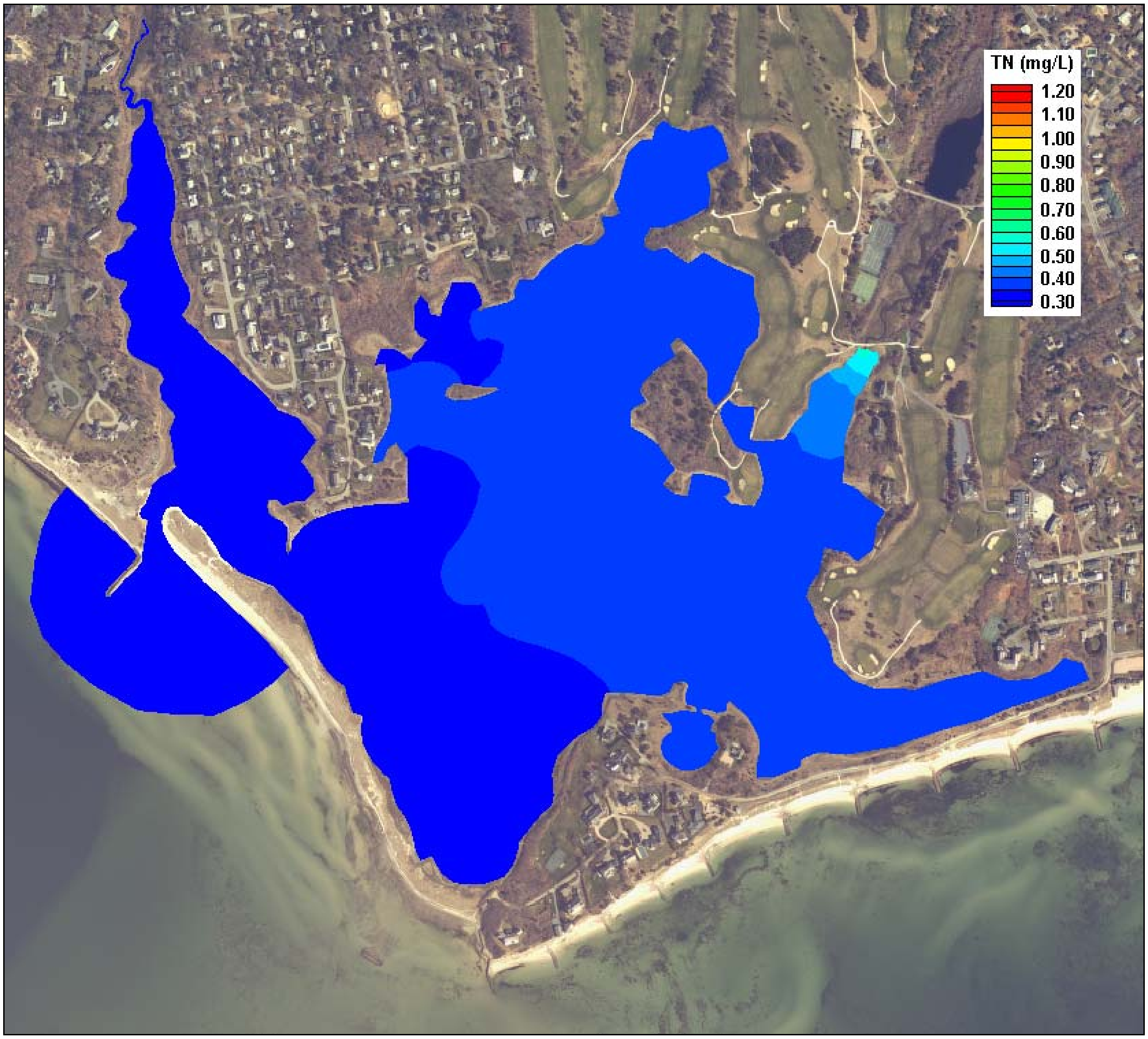


Figure VI-14. Contour plot of modeled total nitrogen concentrations (mg/L) in Halls Creek, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Lewis Bay embayment system (inclusive of Halls Creek) in the Town of Barnstable, MA, our assessment is based upon data from the water quality monitoring database developed by the Town of Barnstable and our surveys of eelgrass distribution, benthic animal communities and sediment characteristics, and dissolved oxygen records conducted during the summer and fall of 2004. 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 these systems (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen thresholds 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 dissolved oxygen sensors within the Lewis Bay main basin (Inner and Outer Lewis Bay and its key tributary sub-embayments (Mill Creek, Uncle Roberts Cove, Hyannis Inner Harbor), to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Lewis Bay system was conducted for comparison to historic records (MassDEP Eelgrass Mapping Program, C. Costello). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the Lewis Bay system, temporal changes in eelgrass distribution provided a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet) in nutrient enrichment.

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

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 3.8 mg L^{-1}, in open water estuarine environments.. Massachusetts State Water Quality Classifications indicate that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Lewis Bay system are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality. It is through the MEP and TMDL processes that management actions are developed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Lewis Bay system (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the Lewis Bay system was collected during the summers of 2003, 2004, and 2006.

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

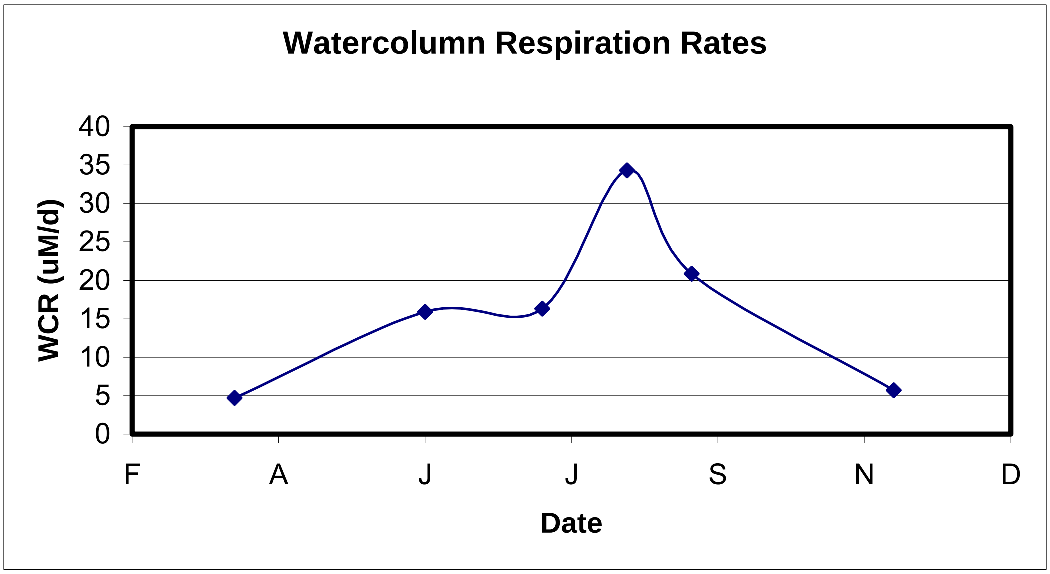


Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Dissolved oxygen and chlorophyll a records were examined both for temporal trends and to determine the percent of the 33-52 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 moderately nutrient enriched waters within each sub-embayment basin (Figures VII-3 through VII-14). The oxygen data is consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll a. The measured levels of oxygen depletion and enhanced chlorophyll a levels follows the spatial pattern of total nitrogen levels in this system (Chapter VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

The oxygen records show that the inner sub-embayments of Mill Creek and Hyannis Harbor, which receive significant watershed nitrogen loads, have the largest daily oxygen excursions, a nutrient related response. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration indicates that the upper tidal reaches of the Lewis Bay system are nitrogen enriched.

Measured dissolved oxygen depletion indicate that sub-embayments to Lewis Bay, Uncle Robert's Cove and to a lesser extent, Hyannis Inner Harbor, show moderate and low levels of oxygen stress. The largest oxygen depletions were observed in Mill Creek, but this is primarily functioning as a salt marsh pond. As such this system is naturally nutrient and organic matter enriched, with oxygen depletions common. The observed spatial pattern indicated that the level of oxygen depletion (Table VII-1) and chlorophyll a (Table VII-2) and total nitrogen levels increased with increasing distance from the tidal inlet and into the smaller sub-embayments. The pattern of oxygen depletion, elevated chlorophyll a and nitrogen levels are consistent with the observed pattern of eelgrass loss (Section VII.3) and quality of infaunal habitats (Section VII.4) and are indicative of an estuarine system that is beyond its ability to assimilate nitrogen loads without impairment. The embayment specific results are as follows:

Hyannis Harbor (west and east) (Figures VII-3 and VII-9; Figures VII-4 and VII-10):

Both Hyannis Harbor moorings were placed in protected areas of the abundant finger piers. A deep channel provides access for ferries and less restriction of tidal water movement in the generally deep water (3-5 meters). The mooring records from the east and west side of the harbor were very similar where the mooring records overlap, however, dissolved oxygen in the west was slightly lower and had a smaller diurnal variation than observed in the east. A similar pattern was seen in the chlorophyll record. The records are consistent with a moderate enrichment of nitrogen and phytoplankton. Differences between the records appear to be a function of water depth and clarity at the two locations. The average depth of the West Hyannis Harbor was 0.75 m deeper than East Hyannis Harbor and while there was a 50% reduction in water column chlorophyll throughout the deployment secchi depths were less than 75 % of the total mooring depth in the west and less than 50% in the east. Deeper deployment depth and lower water clarity at Hyannis Harbor West, possibly influenced by sediment suspension by the ferries, explains the slightly lower DO and chlorophyll as well as less diurnal variation. The mooring records indicate moderate nutrient related impairment.

Mill Creek (Figures VII-5 and VII-11):

The Mill Creek mooring was placed in the middle of the west lobe of Mill Creek at a depth barely sufficient to keep the sensors submerged. Outside of the tidal channel accumulations of drift *Ulva* and *Codium* were moderate to high. It was not possible to ascertain the extent to which the macroalgae was produced within this basin versus that which was transported into the basin on the flood tide. However, as drift *Codium* was observed and it was not growing within the main basins of Mill Pond, it is clear that transport into the basin was occurring. In addition, high chlorophyll concentrations >20 ug L^{-1} (>25 ug L^{-1} 22% of the time) were observed during two weeks in August as a result of a phytoplankton bloom that was occurring system-wide. The bloom was most intense within this shallow basin, but was recorded within all basins. Coincident with this phytoplankton bloom were extreme diurnal variations in dissolved oxygen levels (10 mg L^{-1}). Macroalgal dark respiration resulting from self shading during daylight hours as well as surface water aeration may have been responsible for smaller diurnal variation during the remainder of the deployment. Oxygen concentrations rarely dropped below the benchmark level of 4 mg L^{-1} (2%). The oxygen and chlorophyll a data indicate that Mill Creek is a nutrient enriched salt marsh basin.

Inner Lewis Bay (Figures VII-6 and VII-12):

The Inner Lewis Bay mooring was located in 2.2 m of water within the mooring field 250 m offshore from Englewood Beach (Figure VII-2). Both the chlorophyll a and dissolved oxygen records indicate a moderately nutrient enriched estuarine area. Dissolved oxygen depletion was generally moderate, dropping below the 5 mg L^{-1} benchmark level for only 6% of the deployment interval (Table VII-1). However, the frequency of these short term events was approximately every two days. Diurnal excursions in dissolved oxygen were typically 2-3 mg L^{-1}, but larger (>6 mg L^{-1}) during the senescing period of the phytoplankton bloom (August 10-22). Two of the lowest oxygen concentrations were associated with bloom collapse.. Both moderate to low sediment oxygen uptake rates and sparse to moderate macroalgae coverage at the bottom point to phytoplankton as a dominant contributor to the water column oxygen balance. The mooring data indicate that Inner Lewis Bay is moderately nutrient enriched and moderately impaired based upon these parameters.

Outer Lewis Bay (Figures VII-7 and VII-13)

The Outer Lewis Bay mooring was located in the main Lewis Bay basin towards the tidal inlet, east of the navigation channel (Figure VII-2). Oxygen depletions and chlorophyll enhancement were generally modest, with oxygen levels above 6 mg L^{-1} 82% of the time (Table VII-1) and chlorophyll a concentrations generally below 5 ug/L (75% of record) (Table VII-2). Diurnal variation in oxygen was small rarely exceeding 2 mg L^{-1}. Throughout the deployment air equilibration was ~7.1 mg L^{-1}. Phytoplankton (water column) respiration did not appear to significantly contribute to the oxygen balance at this location. Chlorophyll a levels were low (>5 ug L^{-1} for 25% of the time; Table VII-2) and dissolved oxygen response to blooms (Figure VII-13, Chlorophyll a>6 ug L^{-1}) was minimal. A combination of low to moderate sediment respiration and >80% coverage of macroalgae (*Codium*), was likely responsible for the observed low level of oxygen depletion. By these measures Lewis Bay at the location of the mooring was high quality habitat, without nitrogen related impairment through oxygen depletion. Measurements of Infaunal habitat quality at this location are fully supportive of this assessment (Section VII-4), as this site supports a rich and diverse productive benthic habitat and presently the only eelgrass "patch" inside of the tidal inlet.

Uncle Robert's Cove (Figures VII-8 and VII-14)

Uncle Robert's Cove is a shallow enclosed tributary embayment. The mooring, located in the top third of the embayment at a depth of 1.5 m, showed regular deficits in dissolved oxygen (54% of time <6 mg L^{-1}; 8% of time <5 mg L^{-1}; 1% of time <4 mg L^{-1}, Table VII-1). Diurnal fluctuations in dissolved oxygen were moderate ranging from 1-4 mg L^{-1}. Chlorophyll a levels were moderate to high usually averaging 10 ug L^{-1} with a peak of 30 ug L^{-1} during a bloom near the beginning of the deployment (97%>5 ug L^{-1}; 43%>10 ug L^{-1}, 9%>15 ug L^{-1}; Table VII-2). Dissolved oxygen response to changes in chlorophyll a levels was rapid and significant linking water column processes with changes in dissolved oxygen. Moderate sediment oxygen uptake and low coverage of macroalgae on the bottom (drift filamentous algae) substantiates the importance of water column over sediment processes. Data from Uncle Robert's Cove indicates a moderately to significantly impaired basin resulting from nutrient (and organic matter) enrichment.

Halls Creek

Halls Creek consists of a shallow basin with surrounding salt marsh. No moorings were placed in this basin due to the very low water at low tide. However, the Water Quality Monitoring Program data indicated that in the mid and inlet stations oxygen levels showed only modest levels of depletion with oxygen generally >6 mg L^{-1}, 90% of time, and only 1 record <4.5 mg L^{-1}. Chlorophyll a levels were generally <10 ug L-1 in the mid and inlet stations, 93% and 96% of records (N=30) and showed only moderate levels overall averaging 5.0 and 3.9 ug L^{-1}, respectively compared to 3.6 ug L^{-1} for the adjacent waters of Centerville Harbor. The low level of oxygen depletion for a salt marsh basin and the moderate chlorophyll a concentrations, Halls Creek coupled with the salt marsh structure of this system, is consistent with a high quality habitat.

Figure VII-2. Aerial Photograph of the Lewis Bay system in the Town of Barnstable showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2003. No moorings were placed in Halls Creek, due to the near complete drainage of the creeks and basin at low tide.

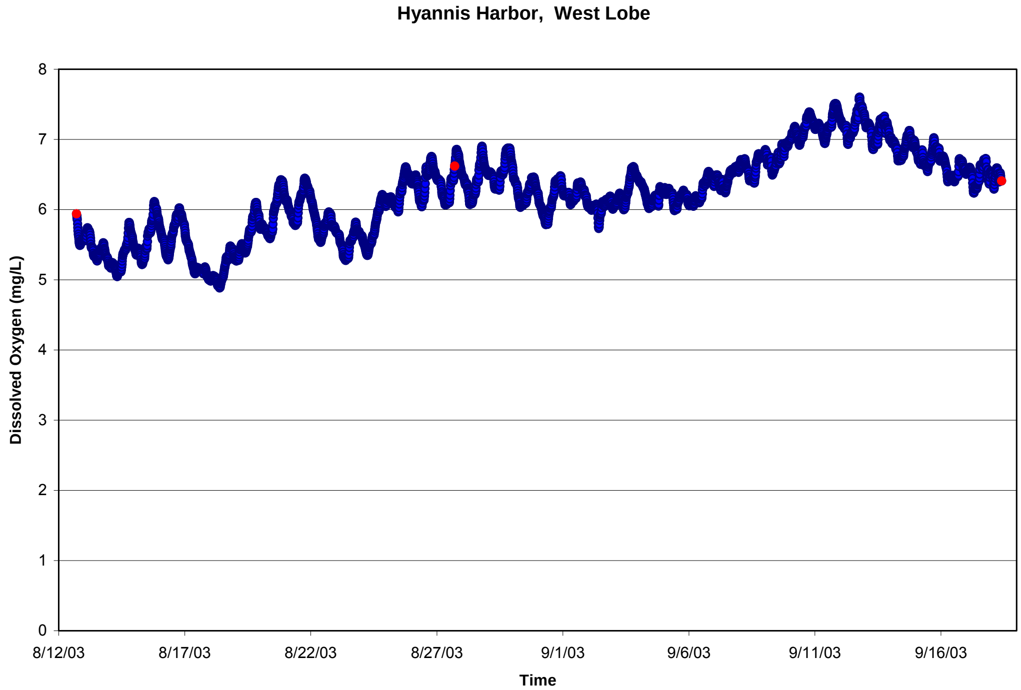


Figure VII-3. Bottom water record of dissolved oxygen at the Hyannis Harbor (west) station, Summer 2003. Calibration samples represented as red dots.

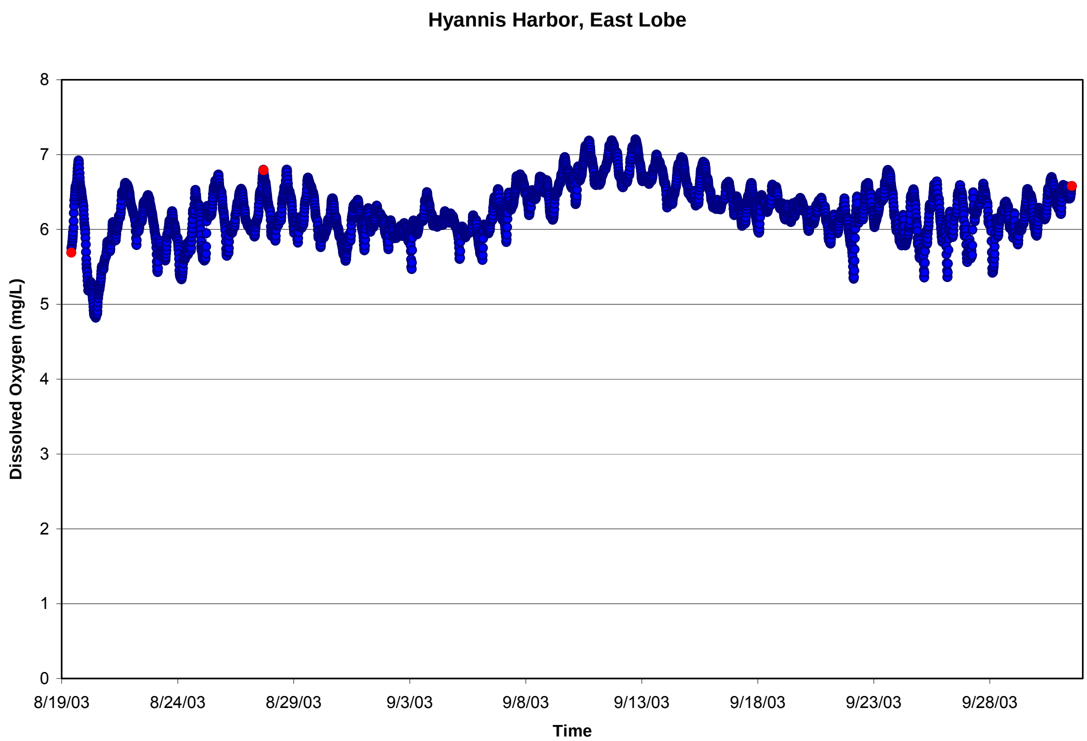


Figure VII-4. Bottom water record of dissolved oxygen at the Hyannis Harbor (east) station, Summer 2003. Calibration samples represented as red dots.

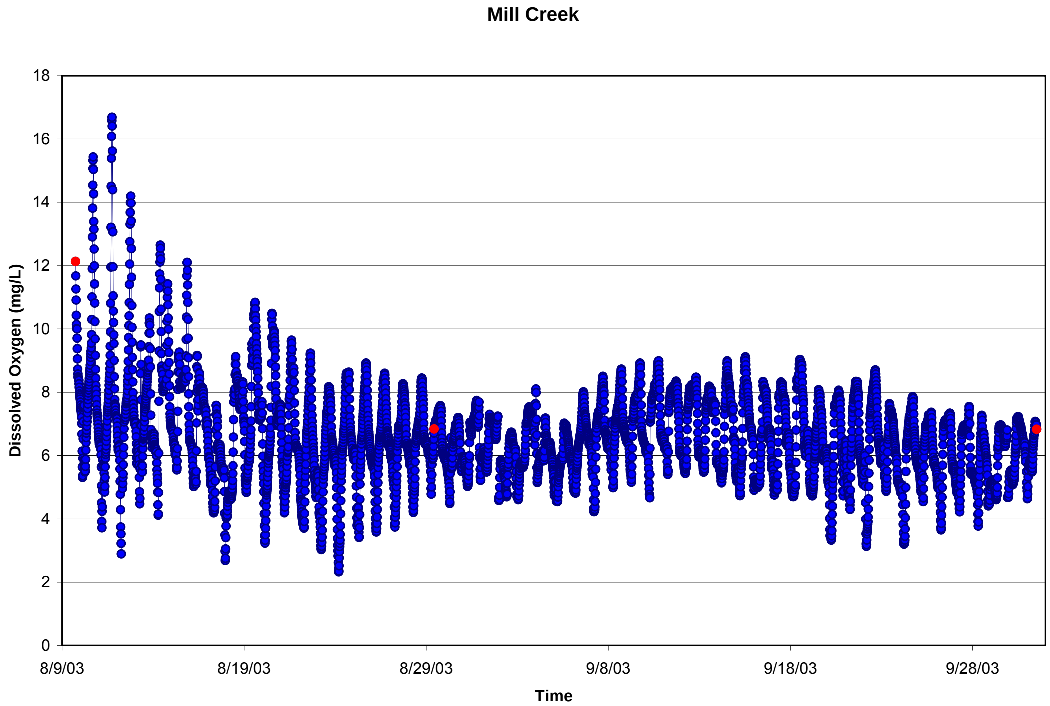


Figure VII-5. Bottom water record of dissolved oxygen at the Mill Creek station, Summer 2003. Calibration samples represented as red dots.

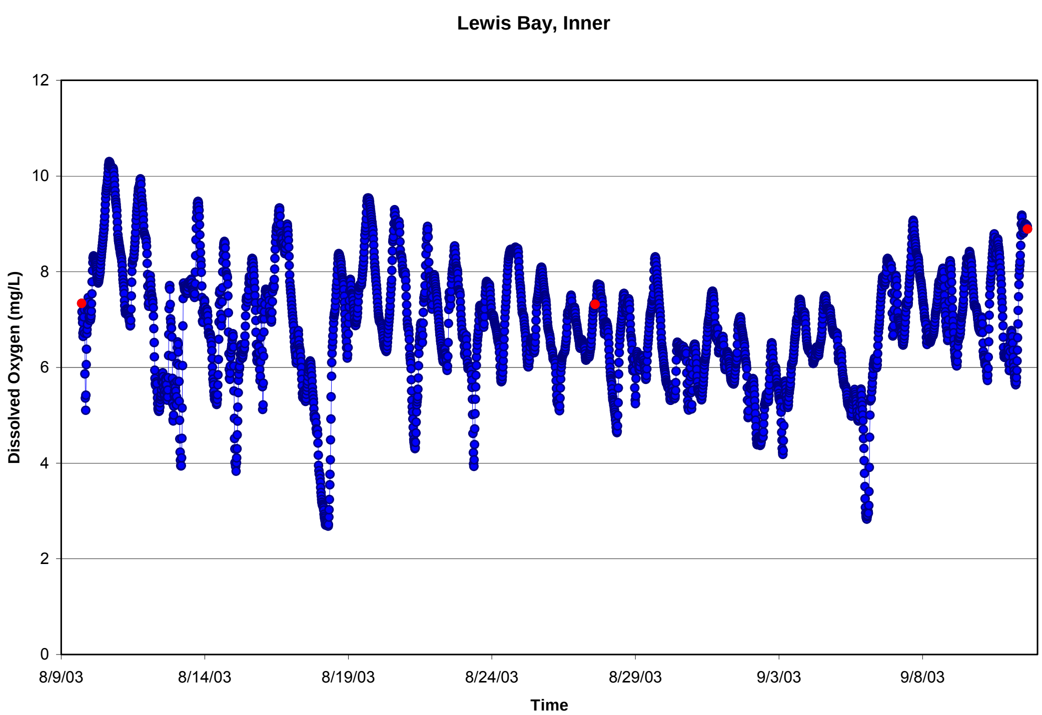


Figure VII-6. Bottom water record of dissolved oxygen at the Lewis Bay (inner) station, Summer 2003. Calibration samples represented as red dots.

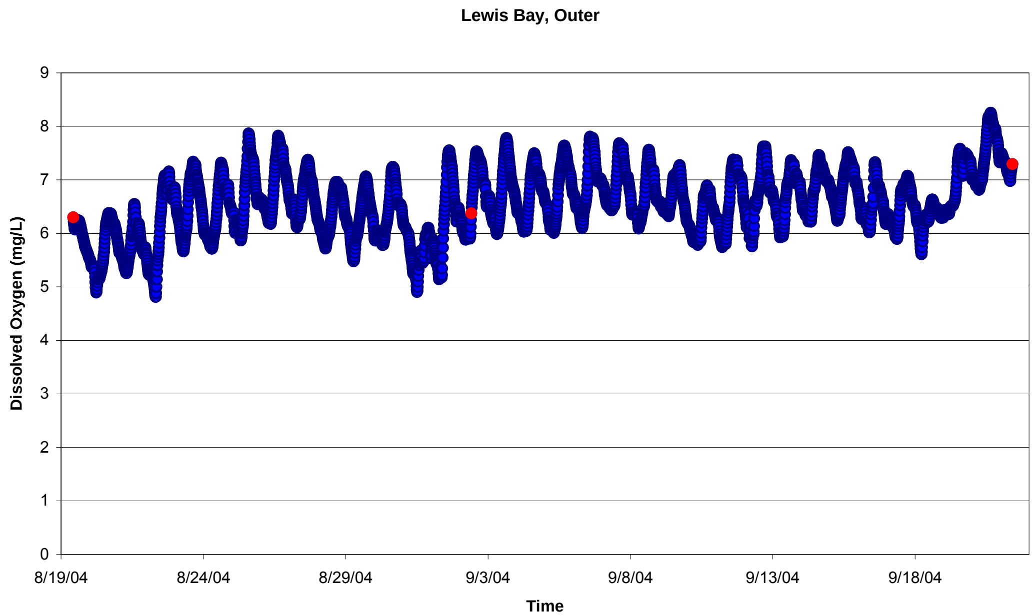


Figure VII-7. Bottom water record of dissolved oxygen at the Lewis Bay (outer) station, Summer 2003. Calibration samples represented as red dots.

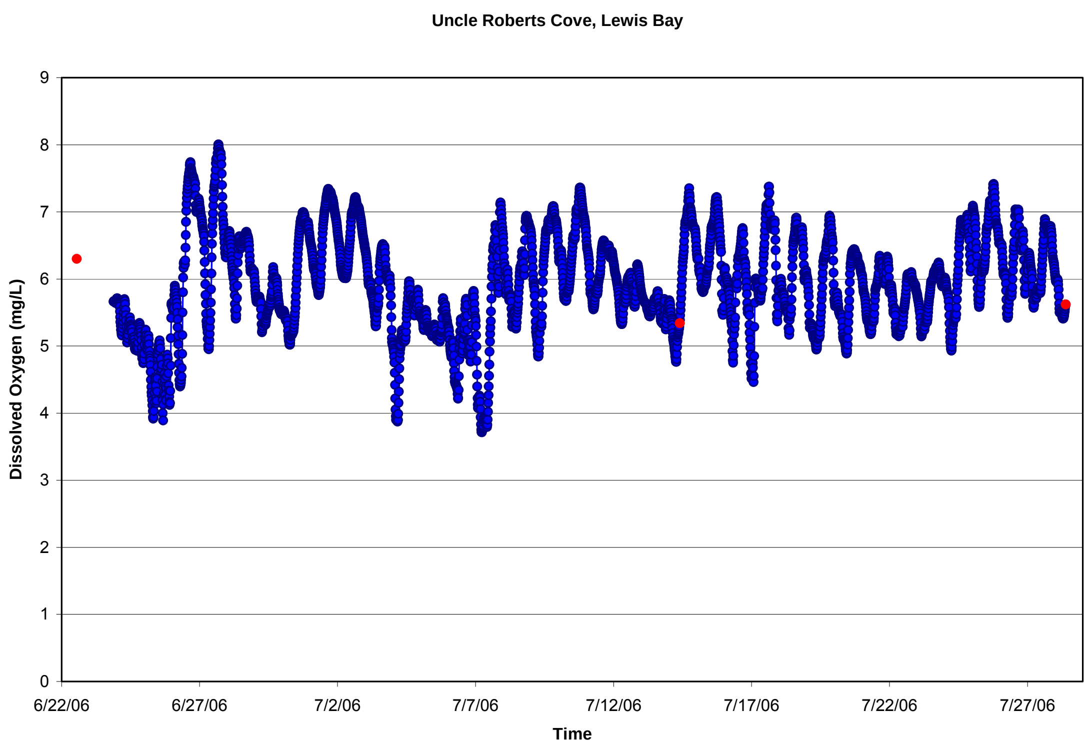


Figure VII-8. Bottom water record of dissolved oxygen at the Uncle Robert's Cove station, Summer 2003. Calibration samples represented as red dots .

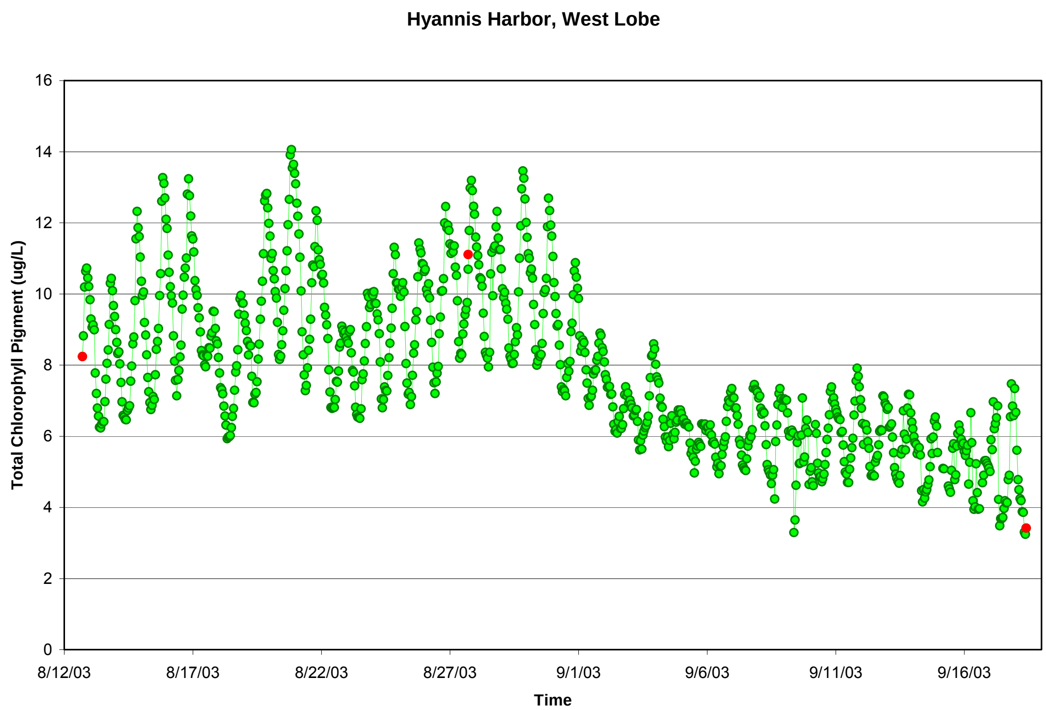


Figure VII-9. Bottom water record of Chlorophyll-*a* in Hyannis Harbor (west) station, Summer 2003. Calibration samples represented as red dots.

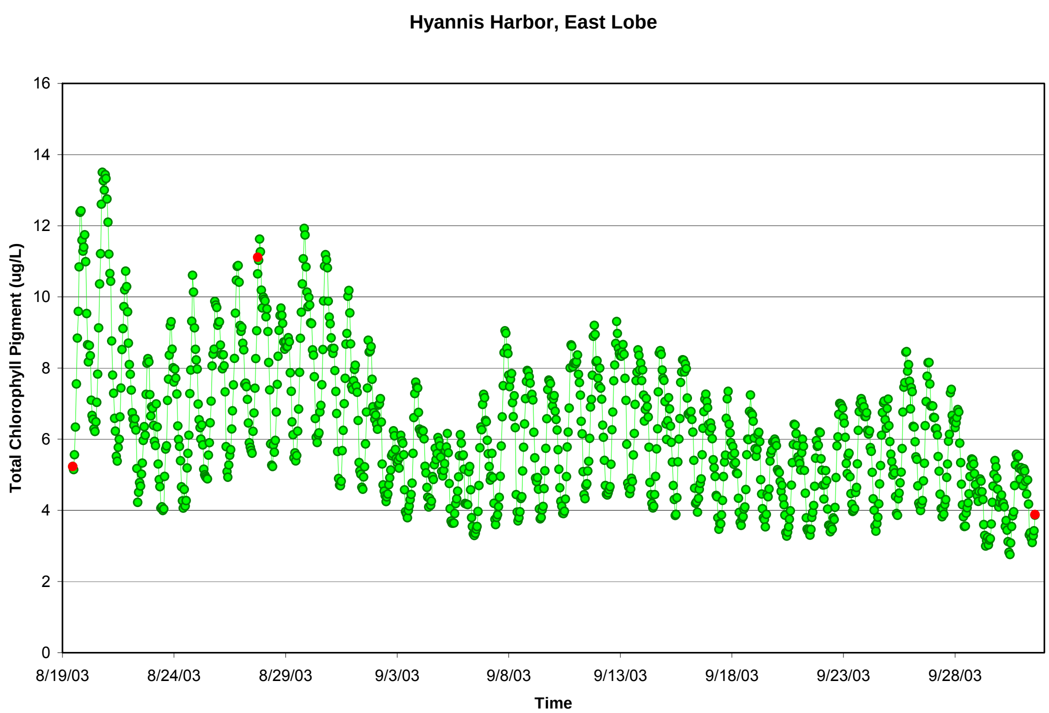


Figure VII-10. Bottom water record of Chlorophyll-*a* in Hyannis Harbor (east) station, Summer 2003. Calibration samples represented as red dots.

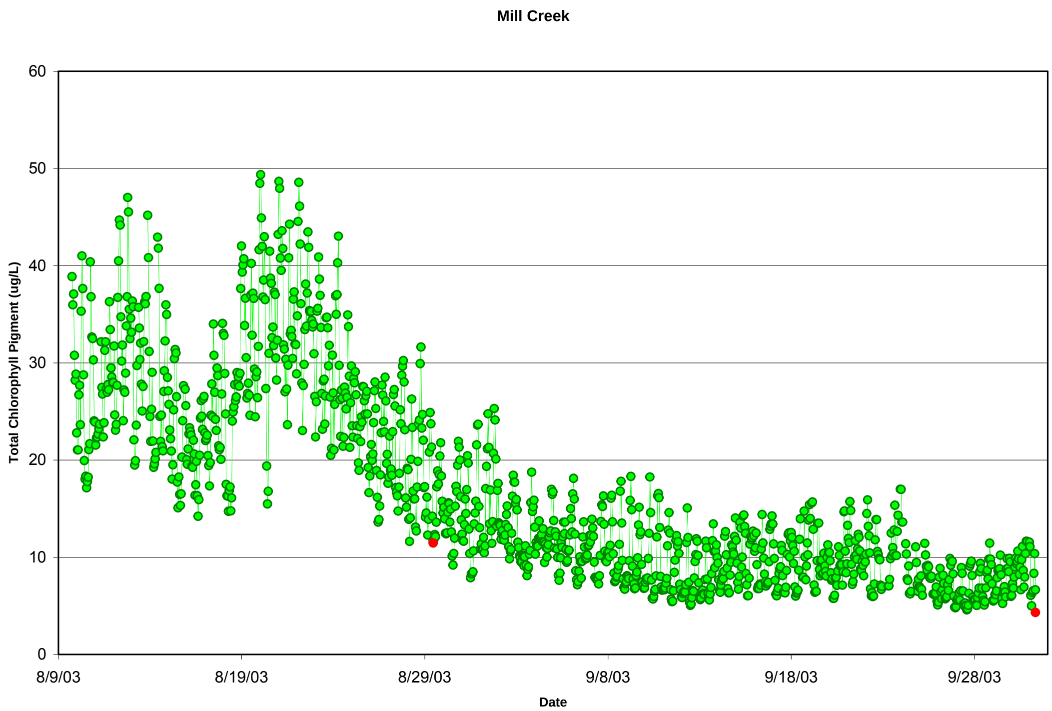


Figure VII-11. Bottom water record of Chlorophyll-*a* in Mill Creek station, Summer 2003. Calibration samples represented as red dots.

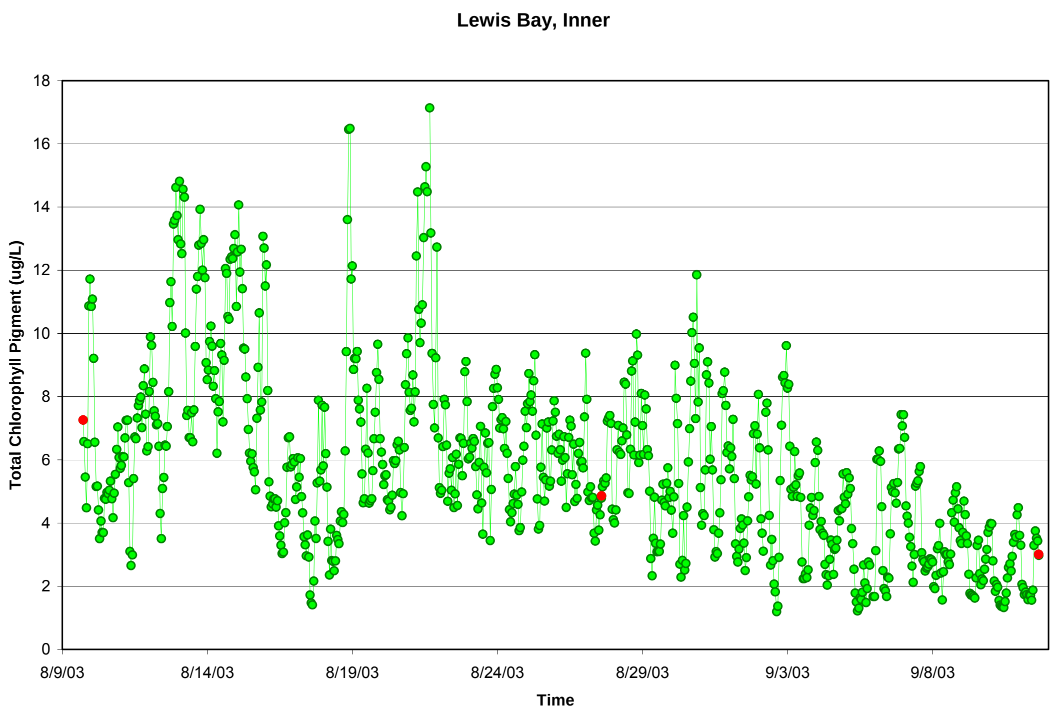


Figure VII-12. Bottom water record of Chlorophyll-*a* in Lewis Bay (inner) station, Summer 2003. Calibration samples represented as red dots.

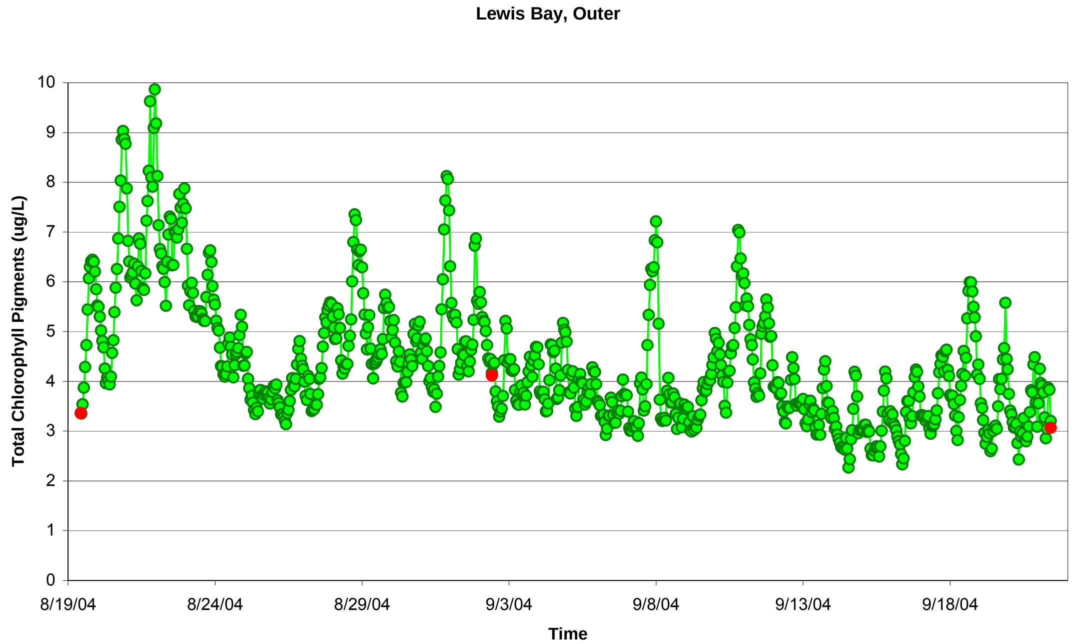


Figure VII-13. Bottom water record of Chlorophyll-*a* in Lewis Bay (outer) station, Summer 2003. Calibration samples represented as red dots.

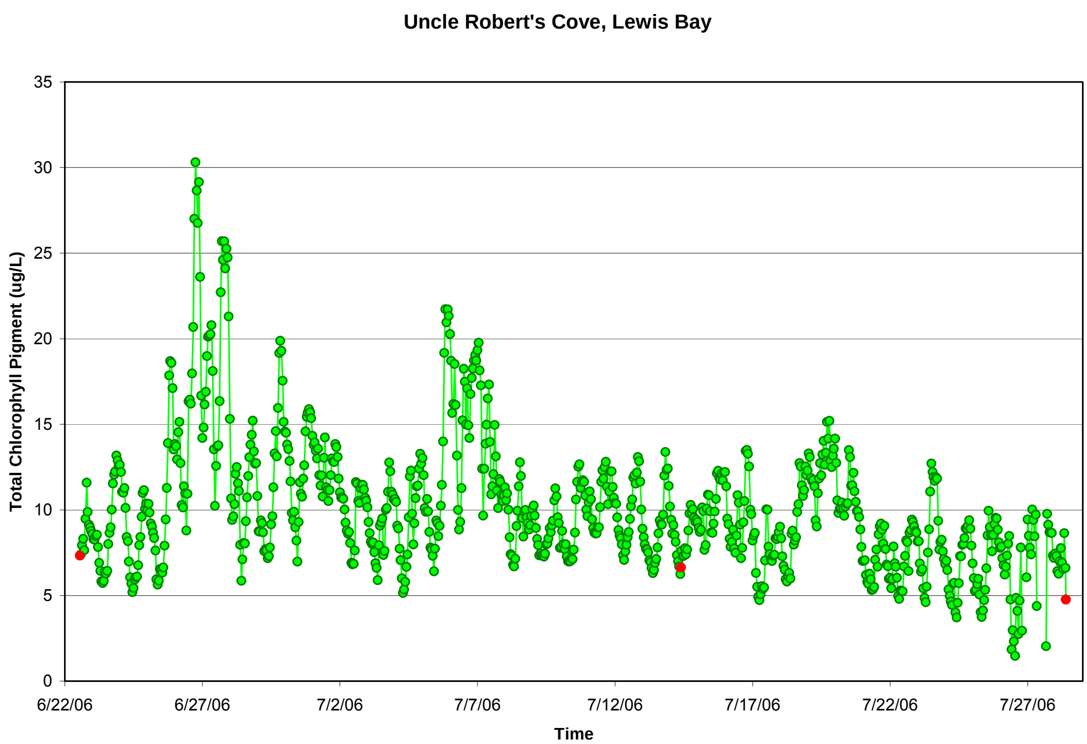


Figure VII-14. Bottom water record of Chlorophyll-*a* in Uncle Roberts Cove station, Summer 2003. Calibration samples represented as red dots.

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

Massachusetts Estuaries Project Town of Barnstable: 2003-04	Dissolved Oxygen: Continuous Record, Summer 2003-04				
	Deployment Days	< 6 mg/L (% of days)	< 5 mg/L (% of days)	< 4 mg/L (% of days)	< 3 mg/L (% of days)
Hyannis Harbor (west)	36.7	30%	1%	0%	0%
Hyannis Harbor (east)	43.1	22%	0%	0%	0%
Mill Creek	52.7	36%	11%	2%	0%
Inner Lewis Bay	33.0	22%	6%	2%	1%
Outer Lewis Bay	33.0	18%	0%	0%	0%
Uncle Robert's Cove	34.5	54%	8%	1%	0%

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

Embayment System	Start Date	End Date	Total Deployment (Days)	> 5 ug/L Duration (Days)	> 10 ug/L Duration (Days)	> 15 ug/L Duration (Days)	> 20 ug/L Duration (Days)	> 25 ug/L Duration (Days)
Lewis Bay								
Hyannis Harbor (west)	8/12/03	9/18/03	36.7	92%	20%	0%	0%	0%
		Mean		1.66	0.30	NA	NA	NA
		S.D.		5.21	0.22	NA	NA	NA
Hyannis Harbor (east)	8/19/03	10/1/03	43.1	69%	5%	0%	0%	0%
		Mean		0.66	0.22	NA	NA	NA
		S.D.		0.78	0.15	NA	NA	NA
Mill Creek	8/9/03	10/1/03	52.7	99%	67%	43%	32%	22%
		Mean		8.51	0.56	0.52	0.55	0.24
		S.D.		18.86	2.61	1.55	0.98	0.24
Lewis Bay Inner	8/9/03	9/11/03	33.0	56%	9%	1%	0%	0%
		Mean		0.35	0.21	0.06	NA	NA
		S.D.		0.53	0.20	0.02	NA	NA

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

Embayment System	Start Date	End Date	Total Deployment (Days)	> 5 ug/L Duration (Days)	> 10 ug/L Duration (Days)	> 15 ug/L Duration (Days)	> 20 ug/L Duration (Days)	> 25 ug/L Duration (Days)
Lewis Bay								
Lewis Bay Outer	8/19/04	9/21/04	33.0	25%	0%	0%	0%	
		Mean		0.42	NA	NA	NA	NA
		S.D.		0.77	NA	NA	NA	NA
Uncle Robert's Cove	6/22/06	7/28/06	34.5	97%	43%	9%	3%	1%
		Mean		3.12	0.38	0.21	0.25	0.08
		S.D.		7.27	0.39	0.17	0.08	0.08

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data was conducted for the Lewis Bay Embayment System by the DEP Eelgrass Mapping Program as part of the MEP. Surveys were conducted in 1995 and 2001, as part of this program. Additional analysis of available aerial photos from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. The 1951 data were only anecdotally validated, while the 1995 and 2001 maps were field validated. The primary use of the data is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 (Figure VII-15 VII-16); the period in which watershed nitrogen loading significantly increased to its present level. This temporal information can be used to determine the stability of the eelgrass community.

At present, eelgrass exists only within a small portion of the system at the tidal inlet of Lewis Bay. Based on the 2001 eelgrass survey, the remaining eelgrass bed appears to be limited to a small area on the margin of the flood tidal delta, to the east of the inlet channel that exits to the man-made basin of Hyannis Harbor (formed by the long breakwater from the western shore). However, large eelgrass beds were observed in the 1951 analysis of aerial photographs, and the recent surveys in the outer basin, Hyannis Harbor. It should be noted that these beds have also declined near the outflow from Lewis Bay. The results of the DEP surveys have been confirmed by multiple MEP staff conducting infaunal animal and sediment sampling and mooring studies. The current decline of eelgrass beds relative to historical distributions is expected given the elevated nitrogen levels and resulting chlorophyll a and dissolved oxygen depletions within this embayment system.

The present absence of eelgrass throughout the Lewis Bay Embayment System is consistent with the observed moderate level of nutrient enrichment throughout each of the sub-embayments to this complex estuary. Total nitrogen levels (TN) within the lower basins that supported eelgrass in 1951, Lewis Bay and Uncle Roberts Cove, have mean summer-time levels of ~0.4 mg N L^{-1} compared to the levels at the outer beds in adjacent Hyannis Harbor of 0.30-0.35 mg N L^{-1} (monitoring data, Chapter VI). Other key water quality indicators, dissolved oxygen and chlorophyll a, show similar levels of moderate enrichment with periodic oxygen depletions below 5-4 mg/L and chlorophyll levels of 3-6 ug/l to 2-10 ug/l in the Lewis Bay basin and 5-15 ug/L in Uncle Roberts Cove. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, the loss of eelgrass in these basins is expected.

Further evidence of nitrogen generated eelgrass decline can be seen in the stability of the eelgrass beds just outside of the tidal inlet to the Hyannis Harbor basin. In each of the MassDEP assessments (1951, 1995, 2001) the major beds along the western shore and outer portion of the eastern shore of Hyannis Harbor showed the same areal coverage. These beds are at the same depths as some of the areas of Lewis Bay that lost eelgrass during the same period. Equally important, the loss of beds nearest the outflow from Lewis Bay did lose coverage, suggesting that the nutrient enriched waters from Lewis Bay were influencing the beds within the ebb tide "plume".

The observed pattern of loss is consistent with nutrient enrichment and it appears that the major environmental differences between the Hyannis Harbor sites and Lewis Bay sites are related to nitrogen enrichment. In estuaries on Cape Cod, the general pattern is for highest nitrogen levels to be found within the innermost basins, with concentrations declining moving toward the tidal inlet. This pattern is also observed in nutrient related habitat quality parameters, like phytoplankton, turbidity, oxygen depletion, etc. The consequence is that eelgrass bed decline typically follows a pattern of loss in the innermost basins (and sometimes also from the deeper waters of other basins) first. The temporal pattern is a “retreat” of beds toward the region of the tidal inlet. It appears from the eelgrass and water quality information that eelgrass beds within Lewis Bay and Uncle Roberts Cove have declined as a result of nitrogen enrichment and should be the target for restoration and that this habitat would be recovered with appropriate nitrogen management.

The other major sub-embayments to the Lewis Bay System do not have evidence of ever having supported eelgrass habitat. The basins of Mill Creek are strongly influenced by surrounding tidal salt marshes and as such do not typically support eelgrass habitat. Salt marsh basins are generally shallow, nutrient and organic matter enriched (as part of their structure and function) and generally show summertime oxygen depletion. All these factors together yields conditions not supportive of eelgrass. Basins like Hyannis Inner Harbor may support eelgrass habitat under low to moderate nitrogen loading conditions. However, this system is a busy working harbor, which is dredged for navigation, lacked eelgrass even in the 1951 analysis, and has no other evidence of eelgrass coverage within the past 75 years. Therefore, the necessary conclusion is that this small basin should not be considered for eelgrass restoration within Lewis Bay System.

Other factors which influence eelgrass bed loss in embayments can also be at play in the Lewis Bay Embayment System, though the recent loss appears completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, as loss in Lewis Bay and Uncle Roberts Cove was observed from both mooring and non-mooring areas. Moreover, much of the basin is not a boat mooring area. Similarly, pier construction and boating pressure may be adding additional stress in nutrient enriched areas, but do not seem to be the overarching factor, especially given structure of these basins and the distribution of docks. It is not possible at this time to determine the potential effect of shellfishing on eelgrass bed distribution, although it should be noted that given the extensive *Codium* beds that have colonized Lewis Bay, this would indicate that disturbance from shell fishing activity is not a major issue at this location.

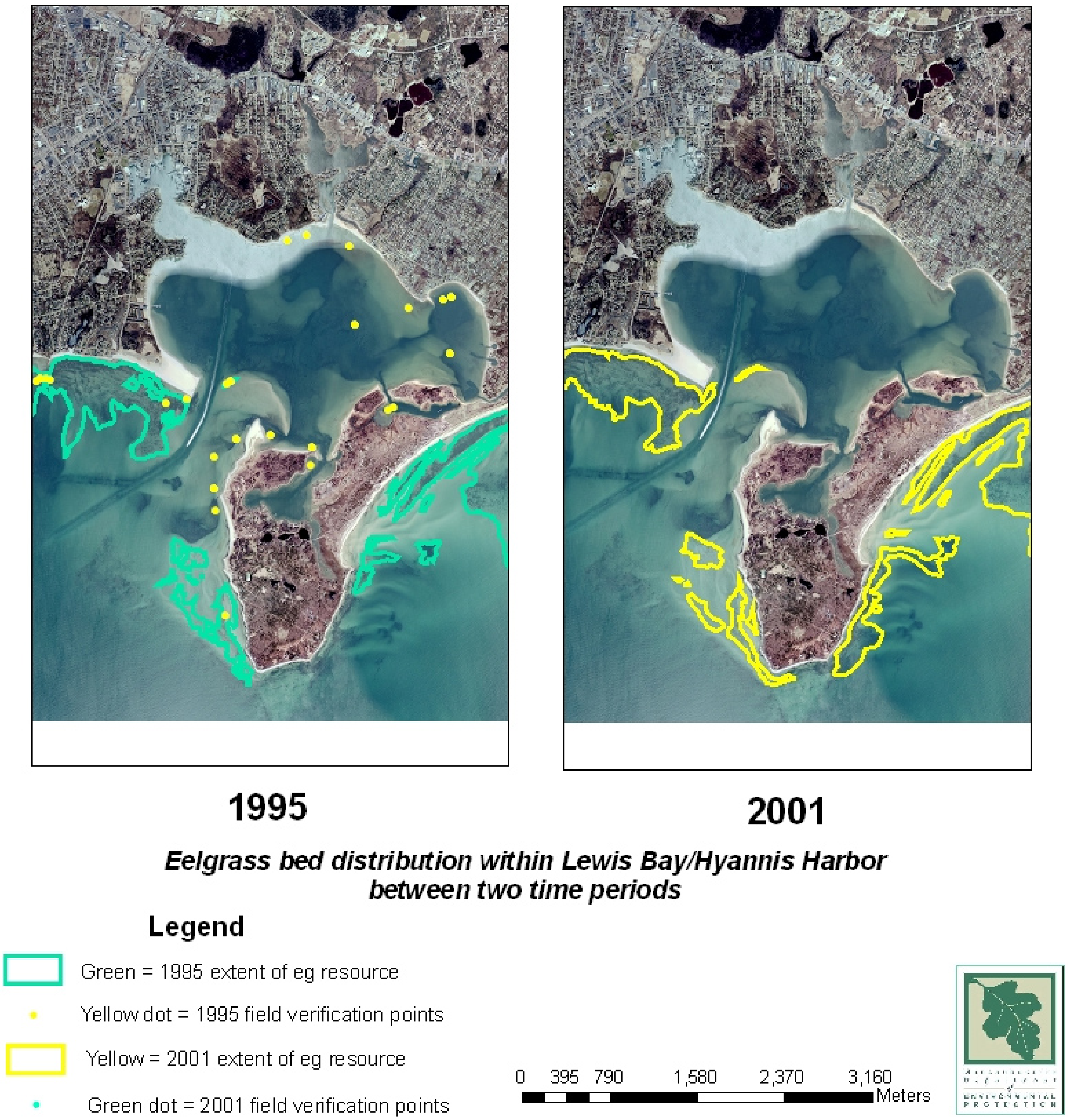


Figure VII-15. Eelgrass bed distribution within the Lewis Bay System. The 1995 coverage is depicted by the green outline inside of which circumscribes the eelgrass beds. The yellow (2001) areas were mapped by DEP. All data was provided by the DEP Eelgrass Mapping Program.

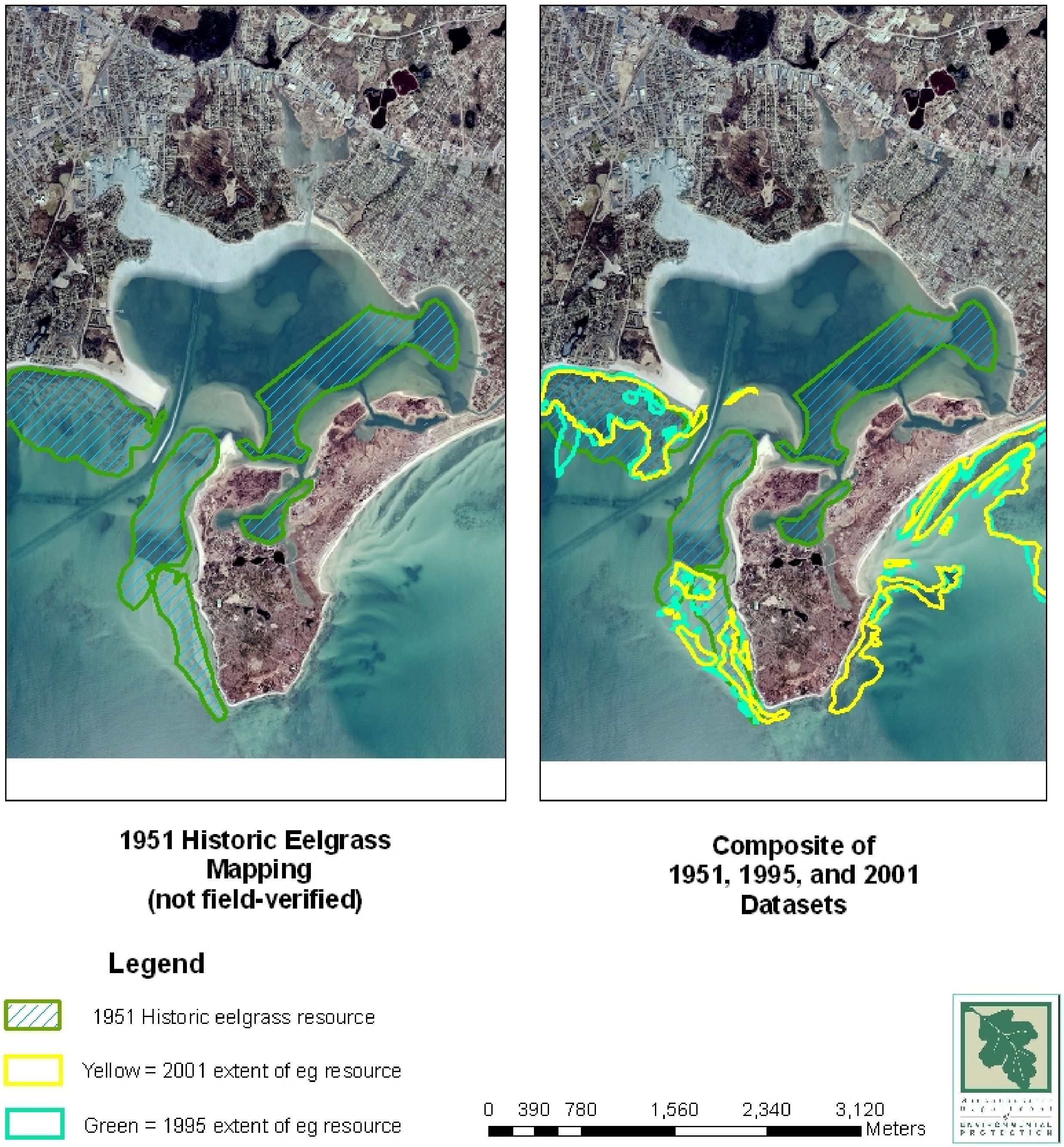


Figure VII-16. Eelgrass bed distribution within the Lewis Bay System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were field verified. All data was provided by the MassDEP Eelgrass Mapping Program.

It is not possible to determine quantitative short- and long-term rates of change in eelgrass coverage from the mapping data, since there is only limited temporal data with virtually no eelgrass found in the recent surveys. However, it is possible to utilize the 1951 coverage data as an indication that a minimum eelgrass bed area that might be recovered (on the order of 200 acres) if nitrogen management alternatives were implemented (Table VII-3). It is likely that a greater area of eelgrass habitat would be restored, as the 1951 coverage is likely an underestimate as a result of mapping problems. Note that restoration of this eelgrass habitat will necessarily result in restoration of other resources throughout the Lewis Bay Embayment System, specifically the shallower eelgrass habitat in Uncle Roberts Cove and the infaunal habitat throughout Lewis Bay and within Hyannis Inner Harbor and Mill Creek. These latter sub-basins have traditionally only supported infaunal habitats (see below).

Table VII-3. Changes in eelgrass coverage in the Lewis Bay Embayment System within the Towns of Barnstable and Yarmouth over the past half century (MassDEP, C. Costello).

Lewis Bay Embayment System: Temporal Change in Eelgrass Coverage			
1951 Acreage	**1995 Acreage**	**2001 Acreage**	**% Loss 1951 to 2001**
216.22	**0.71**	**1.34**	**99%**

There is presently no eelgrass within the Halls Creek Estuary, nor historically. Based upon all available information, it appears that the Halls Creek Estuary is not structured to support eelgrass habitat, similar to Mill Creek and the salt marsh systems of Namskaket Marsh and Little Namskaket Creek in the Town of Orleans. This is typical for New England salt marshes, which are naturally organic and nutrient rich and generally contain little water in the creeks at low tide. This conclusion has been confirmed by the MEP Technical Team in a wide range of salt marsh dominated basins throughout southeastern Massachusetts. Therefore, threshold development for protection/restoration of this system will focus on infaunal habitat quality and the water quality data for this system (see below).

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 14 locations throughout the Lewis Bay Embayment System and 4 locations within Halls Creek (Figure VII-17). In some cases multiple assays were conducted. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the loss of eelgrass beds, the Lewis Bay System is clearly impaired by nutrient overloading. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

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

Lewis Bay Estuary: Overall, the Infauna Survey indicated that most areas within the main Lewis Bay basin are supporting high to moderate quality infaunal habitat. The range of habitat quality within Lewis Bay results from a gradient in nutrient related habitat degradation from the inland reach to the high quality habitat near the tidal inlet. This gradient continues into Hyannis Harbor and Uncle Roberts Cove. While the basin of Mill Creek is naturally nutrient and organic matter enriched, the present conditions of macroalgae and high chlorophyll a levels suggest a moderate level of impairment for this system as well.

The outer stations within Lewis Bay currently support high numbers of individuals distributed among a large number of species (32). The community is composed of a variety of polychaete, crustacean and mollusk species, with high diversity and eveness. The data are clearly indicative of a high quality embayment habitat. Throughout the rest of the large basin of Lewis Bay, infaunal communities are indicative of a high to slightly impaired benthic habitat (in limited areas). The diversity and eveness are generally high, with numerous species and ones generally indicative of high habitat quality.

In contrast, Uncle Roberts Cove had depleted benthic communities (37 individuals/sample), although a moderate number of species were present. This pattern of high diversity, but impoverished numbers has been observed in systems with periodic oxygen stress. But whatever the cause, the benthic habitat quality in this tributary system is clearly significantly impaired. Hyannis Inner Harbor showed infauna typical of a moderately nitrogen enriched basin. The communities were highly spatially variable, with some species found in very high numbers (*Gemma*). However, the number of species remained moderate-high and stress indicator species were not prevalent, so only a moderate level of impairment was evident. The benthic habitat data was consistent with the levels of total nitrogen (0.518-0.574 mg N L^{-1}, tidally averaged) and chlorophyll a and oxygen depletion in this basin.

Mill Creek showed infaunal communities consistent with a salt marsh basin, with moderate numbers of species and individuals, and species indicative of an organic rich environment, but not contamination (i.e. not *Capitella*). Deposit and filter feeders were observed at these sites along with mollusks and crustaceans. The benthic habitat data suggests a high quality infaunal habitat, yet it did appear to be "patchy", potentially the result of drift algae. This variability is cause for concern as it suggests that this system may be moderately impaired. However, in general the habitat appeared typical of larger salt marsh basins in less developed watersheds

Overall, the infaunal habitat quality was consistent with the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to whether it was dominated by wetlands or more representative of a tidal embayment. Based upon this analysis it is clear that the tributary sub-embayment basins are presently supporting moderately to significantly impaired benthic habitat, while the main basin of Lewis Bay is generally of high quality and the Mill Creek basin is supporting moderately impaired habitat for a salt marsh basin. Impairment in these basins is through nitrogen and organic matter enrichment.

The results of the Infauna Survey indicate that the nitrogen management threshold analysis (Chapter VIII) needs o include a lowering of the level of nitrogen enrichment in Hyannis Inner Harbor and Uncle Roberts Cove and potentially in Mill Creek to yield restoration of nitrogen impaired benthic habitats. However, it is important to note that in general the Lewis Bay Embayment System is supportive of high quality infauna habitat throughout much of basin area and that the level of impairment in the tributary sub-embayments is only moderate to low.

Halls Creek Estuary: Infauna communities within the central tidal creek of the Halls Creek Estuary are presently supporting infaunal habitat typical of the organic rich environment of New England salt marshes in summer. The communities are consistent with the observed levels of oxygen depletion and watercolumn TN. The communities within the upper reach had moderate to high numbers of individuals, and moderate species numbers. The communities generally contained some organic enrichment tolerant species. However, species like *Capitella* and tubificids did not dominate as in impaired habitats,, although *Streblospio* was among the dominant species. The diversity was moderate to high 2.14 – 3.41 and generally well distributed (Eveness >0.75). Equally important, the species present were typical of high quality salt marsh habitats, with some crustaceans and mollusks among the dominant polychaetes.

Overall, the Infauna Survey indicated that most areas within the creeks and basin of the Halls Creek Estuary are supporting infauna habitat typical of organic rich New England salt marshes, hence high quality relative to this estuarine ecosystem type. This is supported by the absence of macroalgal accumulations and algal mats within the creek bottoms which can result if there is "excessive" external nitrogen loading. The absence of macroalgal accumulations is consistent with the low total nitrogen levels within this system, 0.385-0.469 mg N L^{-1} (tidally averaged). This is in comparison to a similar marsh, Cockle Cove Creek (Chatham), which supports high quality habitats, both emergent marsh and creek bottom, at levels of 2 mg TN L^{-1}. Based upon all lines of evidence it appears that the Namskaket Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment.

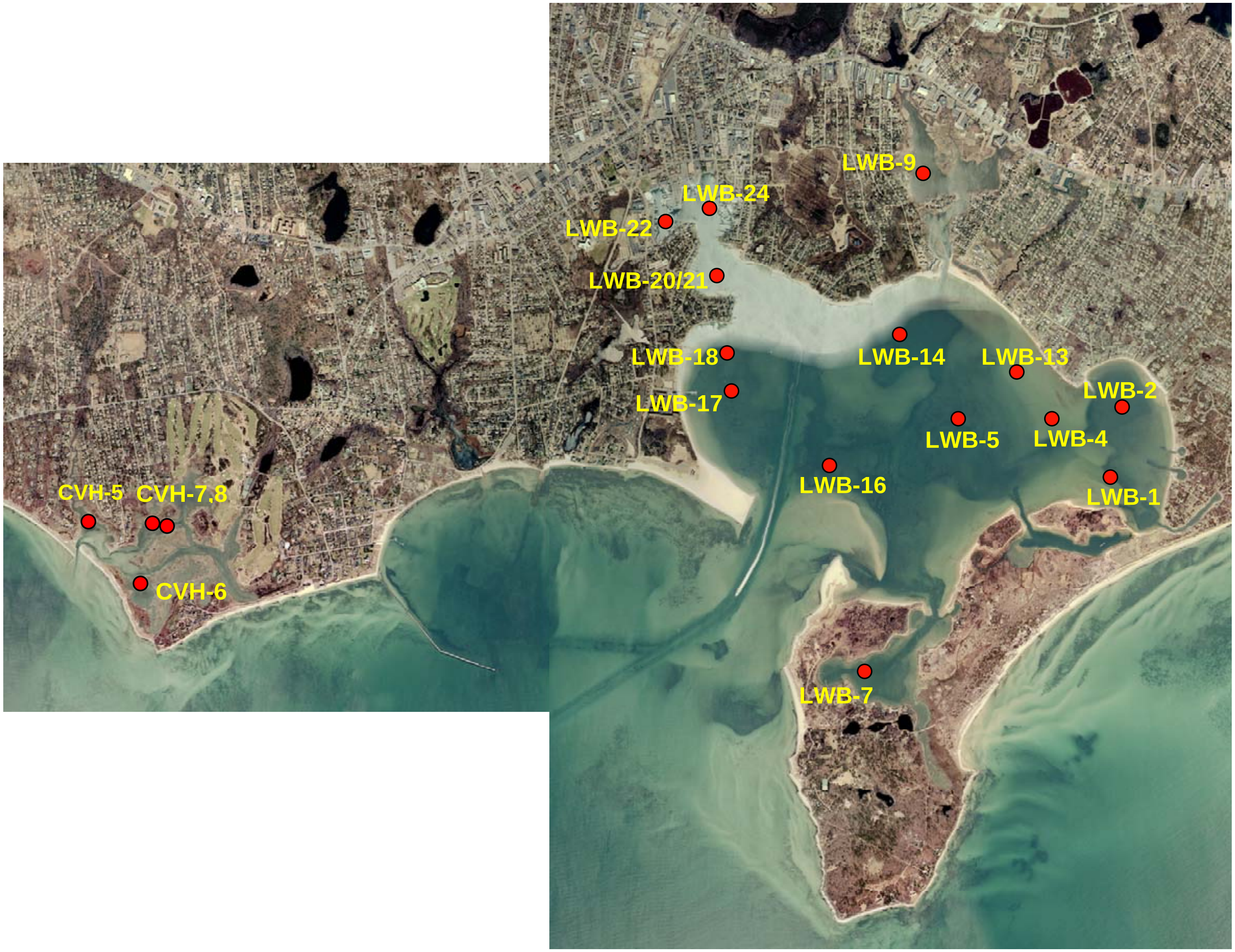


Figure VII-17. Aerial photograph of the Lewis Bay system showing location of benthic infaunal sampling stations (red symbol).

Table VII-4. Benthic infaunal community data for the Lewis Bay embayment system. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.018 m2). Stations refer to map in figure VII-17, (N) is the number of samples per site.

Location	Sta ID (N)	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Lewis Bay						
Eastern Basin	Sta. 1 (2)	6	248	4	1.02	0.33
	Sta. 2 (2)	21	97	19	3.96	0.90
	Sta. 4 (2)	19	185	16	3.45	0.82
Western Basin	Sta. 17 (1)	22	395	12	2.22	0.50
	Sta. 18 (2)	15	97	14	3.48	0.89
Central Basin	Sta. 13 (1)	15	84	14	2.93	0.75
	Sta. 5 (1)	12	64	NA	2.29	0.62
	Sta. 14 (1)	14	60	NA	2.99	0.79
Hyannis Inner Harbor						
	Sta. 22 (2)	16	147	12	2.76	0.70
	Sta. 24 (2)	12	81	15	2.83	0.80
	Sta. 20/21(2)	14	2061	6	1.77	0.52
Uncle Roberts Cove						
	Sta. 7 (2)	11	37	NA	3.05	0.88
Mill Creek						
	Sta. 9 (2)	14	93	14	3.04	0.83
Tidal Inlet						
	Sta. 16 (2)	32	502	18	3.69	0.74
Halls Creek						
	Sta 5	10	164	9.31	2.84	0.86
	Sta. 6	14	202	10.91	2.14	0.56
	Sta. 7	21	191	15.51	3.41	0.78
	Sta. 8	13	207	11.47	2.80	0.76

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll) a). Additional information on temporal changes within each sub-embayment and its associated watershed nitrogen load further strengthens the analysis. These data were collected by the MEP to support threshold development for the Lewis Bay Embayment System and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline Water Quality Monitoring Program coordinated between the Towns of Barnstable and Yarmouth (with technical and analytical support from the Coastal Systems Program at SMAST-UMass Dartmouth).

The Lewis Bay Embayment System is a complex estuary composed of 2 functional types of component basin types: embayments (Lewis Bay, Uncle Roberts Cove, Hyannis Inner Harbor) and a salt marsh pond/embayment (Mill Creek). In addition, associated with the Lewis Bay System is the adjacent Halls Creek Estuary, which like Mill Creek is primarily a salt marsh surrounding an open water basin. Halls Creek was included in the Lewis Bay MEP analysis as it receives nitrogen enriched groundwater resulting from discharge of treated effluent from the Hyannis WWTF. This discharge and almost all of the treated wastewater originates within the Lewis Bay watershed. Each of these 2 functional components (embayment and salt marsh) has different natural sensitivities to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of each system and their ability to support eelgrass beds and specific types of infaunal communities.

At present, the Lewis Bay Embayment System is showing variations in nitrogen enrichment and habitat quality among its various component basins. In general the system is showing healthy to moderately impaired benthic habitat. However, the smaller tributary embayments and limited inner areas of Lewis Bay (e.g. Uncle Roberts Cove, Hyannis Inner Harbor) are presently moderately impaired based upon infaunal habitat criteria. Overall, the dominant habitat issue for this system is the significant impairment of the Lewis Bay basin and Uncle Roberts Cove, based on eelgrass criteria. Historical eelgrass beds have been lost in these areas and eelgrass is virtually non-existent within this system. These significantly impaired habitats comprise ca. 90% of the estuarine area of the Lewis Bay Embayment System. In contrast, the Halls Creek System is presently supporting high quality habitat, representative of a New England salt marsh system. As there is no record of eelgrass within this system, typical of salt marshes, the primary resource within the basin relates to infaunal animal communities.

Eelgrass: The present virtual absence of eelgrass throughout the Lewis Bay Embayment System is consistent with the observed nitrogen and the chlorophyll levels and functional basin types comprising this estuary. Lewis Bay and Uncle Roberts Cove supported extensive eelgrass beds in 1951 under lower nitrogen loading conditions.

Currently, eelgrass exists only within a small portion at the tidal inlet of Lewis Bay. The absence of eelgrass throughout the Lewis Bay Embayment System is consistent with the observed moderate level of nutrient enrichment throughout each of the sub-embayments to this complex estuary. Total nitrogen levels (TN) within the lower basins that supported eelgrass in

1951 (Lewis Bay and Uncle Roberts Cove) have mean summertime levels of ~0.4 mg N L^{-1} compared to the levels at the outer beds in adjacent Hyannis Harbor of 0.30-0.35 mg N L^{-1} (monitoring data, Chapter VI). Other key water quality indicators, dissolved oxygen and chlorophyll a, show similar levels of moderate enrichment with periodic oxygen depletions below 5-4 mg/L and chlorophyll levels of 3-6 ug/l to 2-10 ug/l in the Lewis Bay basin and 5-15 ug/L in Uncle Roberts Cove. Given the sensitivity of eelgrass to declining light penetration resulting from nutrient enrichment and secondary effects of organic enrichment and oxygen depletion, the loss of eelgrass in these basins is expected.

The observed pattern of loss is consistent with nutrient enrichment and it appears that the major environmental differences between the Hyannis Harbor sites and Lewis Bay sites are related to nitrogen enrichment. In estuaries on Cape Cod, the general pattern is for highest nitrogen levels to be found within the innermost basins, with concentrations declining moving toward the tidal inlet. This pattern is also observed in nutrient related habitat quality parameters, like phytoplankton, turbidity, oxygen depletion, etc. The consequence is that eelgrass bed decline typically follows a pattern of initial loss in the innermost basins (and sometimes also from the deeper waters of other basins). The temporal pattern is a “retreat” of beds toward the region of the tidal inlet. It appears from the eelgrass and water quality information that eelgrass beds within Lewis Bay and Uncle Roberts Cove have declined as a result of nitrogen enrichment and should be the target for restoration and that this habitat would be recovered with appropriate nitrogen management. Recovery generally follows the reverse pattern of eelgrass loss, with colonization first in the outer and shallow basin areas and later within the inner basin and tributaries.

The other sub-embayments to the Lewis Bay System do not have evidence of ever having supported eelgrass habitat. The basins of Mill Creek are strongly influenced by surrounding tidal salt marshes and as such, do not typically support eelgrass habitat. Salt marsh basins are generally shallow, nutrient and organic matter enriched based on their structure and function and generally show summertime oxygen depletion, conditions not supportive of eelgrass. Basins like Hyannis Inner Harbor may support eelgrass habitat under low to moderate nitrogen loading conditions. However, this sub-basin to the Lewis Bay system is a busy working harbor, which is dredged for navigation, lacked eelgrass even in the 1951 analysis, and has no other evidence of eelgrass coverage within the past 75 years. The necessary conclusion is therefore that this small basin should not be considered for eelgrass restoration within Lewis Bay System.

It appears from the eelgrass and water quality information that eelgrass beds within the Lewis Bay main basin and Uncle Roberts Cove should be the target for restoration and that this habitat should be recovered with appropriate nitrogen management. From the historical analysis, it appears that more than 212 acres of eelgrass habitat could be recovered, if nitrogen management alternatives were implemented. More acreage recovered is likely, as the analysis of the 1951 aerial photography is likely to have underestimated the acreage of eelgrass habitat within Lewis Bay. Note that restoration of this habitat will necessarily result in restoration of other resources throughout the Lewis Bay Embayment System. Since Uncle Roberts Cove, Hyannis Inner Harbor and Mill Creek all receive flood tidal waters from Lewis Bay, nitrogen management focused on lowering nitrogen levels within this large lagoon will de facto result in a lowering of nitrogen levels throughout the estuarine system. Therefore, an improvement of infaunal habitats in each of the 3 tributary sub-embayments will result. It appears that only limited nitrogen reduction is required as Hyannis Inner Harbor and Mill Creek have traditionally only supported infaunal habitat and are only moderately impaired. Similarly, though Uncle Roberts Cove is considered significantly impaired as a result of losing its eelgrass coverage, its nitrogen levels are presently only 0.4 mg N L^{-1} (tidally averaged) and are controlled primarily by nitrogen levels in flood waters from Lewis Bay and rates of flushing.

Based upon the above analysis, eelgrass habitat was selected as the primary nitrogen management goal for Lewis Bay and Uncle Roberts Cove while infaunal habitat quality was selected as the management target for Hyannis Inner Harbor and possibly Mill Creek. These goals are the focus of the MEP management alternatives analysis presented in Chapter IX.

Water Quality: Overall, the oxygen levels within the major sub-basins to the Lewis Bay Embayment System are indicative of relatively healthy or only moderately impaired conditions. This is based on the definition of the Hyannis Inner Harbor and Mill Pond basins as infaunal habitats (e.g. historically have not supported eelgrass) and consideration of each sub-basins physical structure and natural biogeochemical cycling. Similar to other embayments in southeastern Massachusetts, the inner basins evaluated in this assessment showed high frequency variation, apparently related to diurnal and tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration at each mooring site underscores the need for continuous monitoring within these systems.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate moderately nutrient enriched waters within each sub-embayment basin to Lewis Bay. The oxygen data is consistent with organic matter enrichment, primarily from phytoplankton production, as seen from the parallel measurements of chlorophyll a. The measured levels of oxygen depletion and enhanced chlorophyll a levels match the spatial pattern of total nitrogen concentrations in this system. The parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

The oxygen records show that the inner sub-embayments of Mill Creek and Hyannis Harbor, which receive significant watershed nitrogen loads, have the largest daily oxygen excursions (a nutrient related response). The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration indicates that the upper tidal reaches of the Lewis Bay system are nitrogen enriched. In contrast, oxygen levels within Lewis Bay were generally high and chlorophyll a and total nitrogen showed a low level of enrichment, consistent with the generally high level of infaunal habitat quality and the recent loss of the eelgrass that is more sensitive to nutrient enrichment.

Measured dissolved oxygen depletion indicates that the Lewis Bay sub-embayments, Uncle Robert’s Cove and to a lesser extent, Hyannis Inner Harbor, exhibit moderate levels of oxygen stress. The largest oxygen depletions were observed in Mill Creek, but this is primarily functioning as a salt marsh pond. As such this system is naturally nutrient and organic matter enriched, with oxygen depletions common. The observed spatial pattern indicated increasing levels of oxygen depletion (Table VII-1) and chlorophyll a (Table VII-2), and increased total nitrogen levels with increasing distance from the tidal inlet and into the smaller sub-embayments. The pattern of oxygen depletion, elevated chlorophyll a and nitrogen levels is consistent with the observed pattern of eelgrass loss (Section VII.3) and quality of infaunal habitats (Section VII.4). All the information put together reflects an estuarine system that is beyond its ability to assimilate nitrogen loads without impairment.

Infaunal Communities: The infaunal study indicated an overall system supporting generally healthy to only moderately impaired infaunal habitat relative to the ecosystem types represented (i.e. embayment versus salt marsh creek/pond). The range of habitat quality within Lewis Bay, results from a gradient in nutrient related habitat degradation from the inland reaches to the high quality habitat near the tidal inlet. This gradient continues into Hyannis Harbor and Uncle Roberts Cove. While the basin of Mill Creek is naturally nutrient and organic matter enriched, the present conditions of macroalgae and high chlorophyll a levels suggest a moderate level of impairment for this system as well.

The outer stations within Lewis Bay currently support high numbers of individuals distributed among a large number of species (32). The community is composed of a variety of polychaete, crustacean and mollusk species, with high diversity and eveness. The data are clearly indicative of a high quality embayment habitat. Throughout the rest of the large basin of Lewis Bay, infaunal communities are indicative of a high to slightly impaired benthic habitat (in limited areas). In contrast, Uncle Roberts Cove had depleted benthic communities, a pattern observed in systems with periodic oxygen stress. The benthic habitat in this tributary system is clearly significantly impaired. Hyannis Inner Harbor showed infauna typical of a moderately nitrogen enriched basin. The communities showed high spatial variability, with some species found in very high numbers (*Gemma*). However, the number of species remained moderate-high and stress indicator species were not prevalent, so only a moderate level of impairment was evident. The benthic habitat data was consistent with the levels of total nitrogen (0.518-0.574 mg N L^{-1}, tidally averaged) and chlorophyll a and oxygen depletion in this basin.

Mill Creek showed infaunal communities consistent with a salt marsh basin, with moderate numbers of species and individuals, and species indicative of a nutrient and organic rich environment, but not nutrient contamination (i.e. not Capitella). Deposit and filter feeders were observed at these sites with mollusks and crustaceans. The benthic habitat data suggests a high quality infaunal habitat, but did appear to be "patchy", potentially the result of drift algae. This variability is cause for concern as it suggests that this system may be moderately impaired. However, in general the habitat appeared typical of larger salt marsh basins in less developed watersheds

Overall, the infaunal habitat quality was consistent with the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to it being dominated by wetlands versus being more characteristic of a tidal embayment. Based upon this analysis it is clear that the tributary sub-embayment basins are presently supporting moderately to significantly impaired benthic habitat, while the main basin of Lewis Bay is generally of high quality. The Mill Creek basin is supporting moderately impaired habitat for a salt marsh basin. Impairment in these basins is through nitrogen and organic matter enrichment.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Lewis Bay Embayment System on Nantucket Sound within the Towns of Barnstable and Yarmouth, MA., based upon assessment data presented in Chapter VII. The main basin of Lewis Bay and its tributary sub-embayments of Hyannis Inner Harbor and Uncle Roberts Cove are typical coastal embayment basins. In contrast, Mill Creek is primarily a salt marsh basin.

Health Indicator	Lewis Bay Embayment System					
	Lewis Bay		Uncle Roberts Cove	Hyannis Inner Harbor	Mill Creek	Halls Creek
	Outer	Inner				
Dissolved Oxygen	H-MI[2]	MI-SI[3]	MI-SI[4]	H-MI[2]	H-MI[1, 15]	H[24]
Chlorophyll	H-MI[5]	MI[6]	MI-SI[7]	MI[6]	MI[8]	H[5]
Macroalgae	MI[9]	MI[9]	MI[10]	--[11]	MI[12]	--[11]
Eelgrass	SI[13]	SI[13]	SI[13]	--[14]	--[14]	--[14]
Infaunal Animals	H[16]	H-MI[17]	SI[18]	MI[19]	H[20]	H[20]
Overall:	**SI[21]**	**SI[21]**	**SI[21]**	**MI[22]**	**MI[23]**	**H**

1 – primarily a salt marsh pond, periodic oxygen depletions to <4 mg/L, very rarely to 3-2 mg/L.
2 – oxygen levels generally >6 mg/L, with periodic depletions 6-5 mg/L.
3 – oxygen depletions periodically 4-3 mg/L, generally >5 mg DO/L.
4 -- oxygen depletions periodically to 4-4.5 mg/L, with infrequent declines to 3.7 mg/L.
5 – low to moderate chlorophyll a levels generally 3-6 ug/L, generally <5 ug/L 73% of time.
6 – moderate chlorophyll a levels generally ~3-10 ug/L, generally >5 ug/L frequently >10 ug/L
7 – elevated chlorophyll a levels generally 5-15 ug/L, frequently >13 ug/L
8 – high chlorophyll a levels generally >10 ug/L, frequently >20 ug/L
9 – extensive attached dense bed of *Codium* throughout basin, serving as SAV.
10 -- moderate amounts of filamentous drift algae
11 -- drift algae sparse or absent, little surface microphyte mat.
12 -- moderate to high levels of drift algae, Ulva and Codium some in situ, some transported in
13 -- eelgrass lost from this system between 1951-1995.
14 – no evidence this basin is supportive of eelgrass.
15 -- basin supports fringing salt marsh areas.
16 -- Inlet: high numbers, diversity, eveness, large #'s polychaete, crustacean, mollusk species
17 -- moderate numbers of species and high-moderate number individuals; high-moderate diversity and eveness; with polychaetes, mollusks and crustaceans
18 -- low numbers of species and individuals, organic enrichment indicators
19 -- moderate-high (*Gemma*) numbers of individuals, moderate species, moderate H' & Eveness
20 -- Infauna: moderate numbers of individuals, moderate species, high diversity and Eveness; organic enrichment indicators typical of salt marsh ponds, some deep burrowers.
21 -- Significant Impairment based upon loss of eelgrass from system, 1951-1995.
22 -- Moderate Impairment based upon moderate oxygen depletion, elevated chlorophyll; variable infaunal communities, with wide range of numbers, moderate numbers of species with organic enrichment indicators (*Spionids, Gemma, Mullinia*).
23 -- Moderate Impairment based primarily on the high sustained chlorophyll levels.
24 – No moorings were deployed, monitoring data showed moderate depletion of oxygen.

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

The results of the infauna survey indicate that the nitrogen management threshold analysis (Section VIII.2) needs to include a lowering of the level of nitrogen enrichment in Hyannis Inner Harbor and Uncle Roberts Cove and potentially in Mill Creek thereby leading to restoration of nitrogen impaired benthic habitats. However, it is important to note that in general the Lewis Bay Embayment System is supportive of high quality infauna habitat throughout much basin area. Although there are some moderately impaired infaunal habitats within the Lewis Bay Embayment System, restoration needs to also target eelgrass habitat. While most of Lewis Bay shows high quality infauna habitat, it is clearly significantly impaired based on eelgrass criteria, since historical eelgrass beds have been recently lost. As a result, both eelgrass and infaunal animal habitats are impaired in this estuary, and nitrogen management is required for their restoration.

All of the key habitat indicators are consistent within the Halls Creek Estuary, and particularly its tidal creeks, supporting high quality habitat in line with the system's salt marsh structure and function (Chapter VII). Similar to other salt marshes throughout the region, Halls Creek does not appear structured to support eelgrass beds. In contrast, the systems is presently supporting high quality infaunal animal habitat typical of organic rich New England salt marshes, hence high quality relative to this estuarine ecosystem type. This is consistent with the absence of significant accumulations of drift macroalgae within the creek bottoms which can result if there is "excessive" external nitrogen loading. The absence of macroalgal accumulations is consistent with the low levels of total nitrogen within this system, 0.385-0.469 mg N L^{-1}-1 (tidally averaged). Based upon all lines of evidence it appears that the Halls Creek Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment.

VIII.2. THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout an embayment system, is to first identify a sentinel location within the embayment and second to determine the nitrogen concentration within the water column which will restore that 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, the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved.

Determination of the critical nitrogen thresholds for maintaining high quality habitat within Lewis Bay Embayment System and Halls Creek are based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. Given such a database, it is possible to develop a site-specific threshold, which is a refinement upon more general threshold analyses frequently employed.

Lewis Bay Estuary: The Lewis Bay Embayment System presently supports a range of infaunal habitat quality. Within Lewis Bay, a gradient in nutrient related habitat degradation was observed from the inland reach to the high quality habitat near the tidal inlet. This gradient continues into Hyannis Harbor and Uncle Roberts Cove. While the basin of Mill Creek is naturally nutrient and organic matter enriched, the present conditions of macroalgae and high chlorophyll a levels suggest a moderate level of impairment for this system as well. However, the primary habitat issue within the Lewis Bay Embayment System relates to the loss of the extensive eelgrass beds from Lewis Bay and the shallow marginal beds from Uncle Roberts Cove. This loss of eelgrass classifies these areas as "significantly impaired", although Lewis

Bay presently supports generally high quality infaunal communities. The impairments to both the infaunal habitat and the eelgrass habitat within the component basins of the Lewis Bay Embayment System are supported by the variety of other indicators, oxygen depletion, chlorophyll, and TN levels, all of which support the conclusion that these impairments are the result of nitrogen enrichment, primarily from watershed nitrogen loading.

The habitat assessment data are also internally consistent. For example, the observed loss of eelgrass, and continuing presence of SAV (*Codium*) within the Lewis Bay basin, suggests a system not far above its nitrogen threshold level supportive of eelgrass. The tidally averaged nitrogen levels throughout Lewis Bay were found to range from 0.385-0.415 mg N L^{-1}, compared to the inlet station (adjacent existing beds) that supported a TN concentration of 0.369 mg N L^{-1} (tidally averaged). Similarly, the moderate impairment of infaunal habitat in the inner basins of Hyannis Inner Harbor is consistent with the moderate levels of oxygen depletion, chlorophyll a enhancement and tidally averaged total nitrogen levels of 0.518-0.574 mg N L^{-1}.

Only Uncle Roberts Cove can be classified as having both significantly impaired eelgrass and infaunal habitats. The observed loss of eelgrass is consistent with the observed oxygen depletions and elevated chlorophyll and total nitrogen levels (0.432 mg N L^{-1}). The impairment to infauna appears to be related to structural features of the inner basin that provide for a depositional environment and supports periodic stratification and oxygen depletion. The effect of the sedimentation of the inlet to the Cove in enhancing the impacts of nitrogen enrichment in this basin needs to be evaluated. However, as the infaunal community is presently diverse, small reductions in organic matter deposition to reduce the level of oxygen depletion will likely be sufficient to restore this habitat.

The results of the water quality and infaunal data, coupled with the temporal trends in eelgrass coverage, clearly support the need to lower nitrogen levels within Lewis Bay and Uncle Roberts Cove in order to restore eelgrass habitat. Lesser loading reductions would be necessary within Hyannis Inner Harbor and potentially in Mill Creek for restoration of nitrogen impaired benthic habitats. Restoration of the limited areas of moderately impaired and areas of significantly impaired infaunal habitats within Lewis Bay and Uncle Roberts Cove, respectively, will be achieved with the restoration of eelgrass habitat within these basins.

Considering the eelgrass and water quality information it is clear that eelgrass beds within the Lewis Bay basin should be the primary target for restoration of the Lewis Bay Embayment System and that restoration would require appropriate nitrogen management. From the historical analysis, it appears that at least 200 acres of eelgrass habitat could be recovered, if nitrogen management alternatives are implemented. Therefore, the sentinel station (BHY-3) for the Lewis Bay Embayment System was selected based upon its location within the inner region of documented eelgrass coverage in this estuary. The sentinel station is within the mid basin of the easternmost basin of Lewis Bay (sometimes called Little Lewis Bay), between Pine Island and Englewood Beach and is a long-term sampling station of the Yarmouth/Barnstable Water Quality Monitoring Program.

The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location within Lewis Bay was determined to be 0.38 mg TN L^{-1}. As there is not high quality eelgrass habitat within the Lewis Bay Embayment System, this threshold was based upon comparison to other local embayments of similar depths and structure under MEP analysis as well as conditions near the eelgrass areas adjacent the tidal inlet to Hyannis Harbor. A well studied eelgrass bed within the lower Oyster River (Chatham) has been stable at a tidally averaged water column TN concentration of 0.37 mg N L^{-1}, while eelgrass was lost within the

Lower Centerville River at a tidally averaged TN concentration of 0.395 mg N L^{-1}, and also lost within Waquoit Bay at 0.39 mg N L^{-1}. The nitrogen threshold for the lower main basin of Popponesset Bay and for the complex Stage Harbor System was 0.38 mg N L^{-1}. These latter 2 systems have a similarly complex multiple component structure to the Lewis Bay System. These values from other Cape Cod embayments are consistent with the data from Lewis Bay. Eelgrass beds still exist to the west of the inlet to Lewis Bay within Hyannis Harbor. These beds are exposed to tidally averaged nitrogen levels of 0.37 mg N L^{-1}, similar to that in the Oyster River (Chatham). In addition, extensive SAV (*Codium*) persists within the main basin of Lewis Bay which has a basin-wide tidally averaged TN concentration of 0.393 mg N L^{-1} (range 0.385-0.408 mg N L^{-1}). These site specific data indicate that the threshold for eelgrass in this system is between 0.370 and 0.393 (or 0.385) mg N L^{-1}, tidally averaged TN. This is strong support for the 0.380 mg N L^{-1} value determined for the sentinel station (BHY-3). Restoration of the shallow marginal eelgrass habitat within Uncle Roberts Cove allows a higher TN threshold than within the deeper habitat of Lewis Bay.

The selection of the TN level for the shallow marginal bed within Uncle Roberts Cove followed the process noted above for the sentinel station. Since water depth is important in determining the criteria for eelgrass restoration, as the same phytoplankton concentration that results in shading of eelgrass in deep water will allow sufficient light to support eelgrass in shallow water, the shallower water at the upper basin site allows for a higher TN level compared to the sentinel station. Analysis of comparable beds within the Green Pond Estuary (Falmouth) recommends the secondary criteria for this site to be 0.40 mg TN L^{-1} for stability. The target nitrogen concentration for restoration of eelgrass within the lower basin of Green Pond, was determined to be 0.40 mg TN L^{-1} based in part upon the findings that: (1) eelgrass beds have been lost in that basin at 0.41 mg TN L^{-1}, although sparse eelgrass were observed adjacent the inlet, (2) eelgrass beds in Bournes Pond in very shallow water persisted at 0.42 mg TN L^{-1}. It should be noted that 0.40 mg N L^{-1} within Uncle Roberts Cove is a secondary criteria to ensure restoration of eelgrass habitat within this sub-embayment and should be met when the threshold is met at the sentinel station in Lewis Bay. Nitrogen management specific to the watershed of Uncle Roberts Cove will likely not be required, although it will be important to maintain unrestricted tidal exchange to this basin. The sentinel station under present loading conditions supports a tidally averaged concentration of 0.408 mg TN L^{-1}, so watershed nitrogen management will be required for restoration of the estuarine habitats within this system.

Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fisheries resources), benthic infaunal habitat quality must also be supported as a secondary condition. At present, the regions with moderately impaired infaunal habitat within the Hyannis Inner Harbor and the potentially impaired habitat within Mill Creek have total nitrogen (TN) levels in the range of 0.518 - 0.574 mg N L^{-1}. The observed moderate impairment at these sites is consistent with observations by the MEP Technical Team in other enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg N L^{-1} were found to be supportive of healthy infaunal habitat and in deeper enclosed basins in Buzzards Bay (e.g. Eel Pond in Bourne) where healthy infaunal habitat had a slightly lower threshold level, 0.45 mg N L^{-1}, due to it being a "deep" depositional basin. Similarly, the Centerville River system showed moderate impairment at tidally averaged TN levels of 0.526 mg N L^{-1} in Scudder Bay (analogous to Mill Creek) and at 0.543 mg TN L^{-1} in the middle reach of the Centerville River. Additionally, moderate impairment was also observed at the same TN levels (0.535-0.600 mg N L^{-1}) within the Wareham River, with high quality infaunal animal habitat at TN levels of 0.444-0.463 mg TN L^{-1}. Based upon these observations, the MEP Technical Team concluded that an upper limit of 0.50 mg N L^{-1} tidally averaged TN would support healthy infaunal habitat in the Lewis Bay System.

For restoration of the Lewis Bay Embayment System, both the primary nitrogen threshold at the sentinel station and the secondary criteria within the sub-embayments need to be achieved. However, the secondary criteria established by the MEP are to merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station. Three secondary criteria were established for the Lewis Bay Embayment System: (1) a TN level of 0.40 mg N L^{-1} was set to restore the shallow marginal eelgrass bed within Uncle Roberts Cove (tidal average at BHY-4), this will also ensure restoration of infaunal habitat throughout that basin; (2) a tidally averaged TN level of <0.5 mg N L^{-1} with the Hyannis Inner Harbor basin (average of BH-1 and BH-2) and (3) a tidally averaged TN level of <0.5 mg N L^{-1} within the salt marsh basin of Mill Creek to reduce the magnitude of the phytoplankton blooms and improve infaunal habitat in the lower basin.

It should be emphasized that these secondary criteria values were not used for setting nitrogen thresholds in this embayment system. These values merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station. The results of the Linked Watershed-Embayment modeling are used to ascertain that when the nitrogen threshold is attained, TN levels in these regions are within the acceptable range. The goal is to achieve the nitrogen target at the sentinel location and restore eelgrass habitat throughout Lewis Bay and Uncle Roberts Cove as well as infaunal habitat throughout the System. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations are discussed in Section VIII.3, below and depicted in Figure VIII-1.

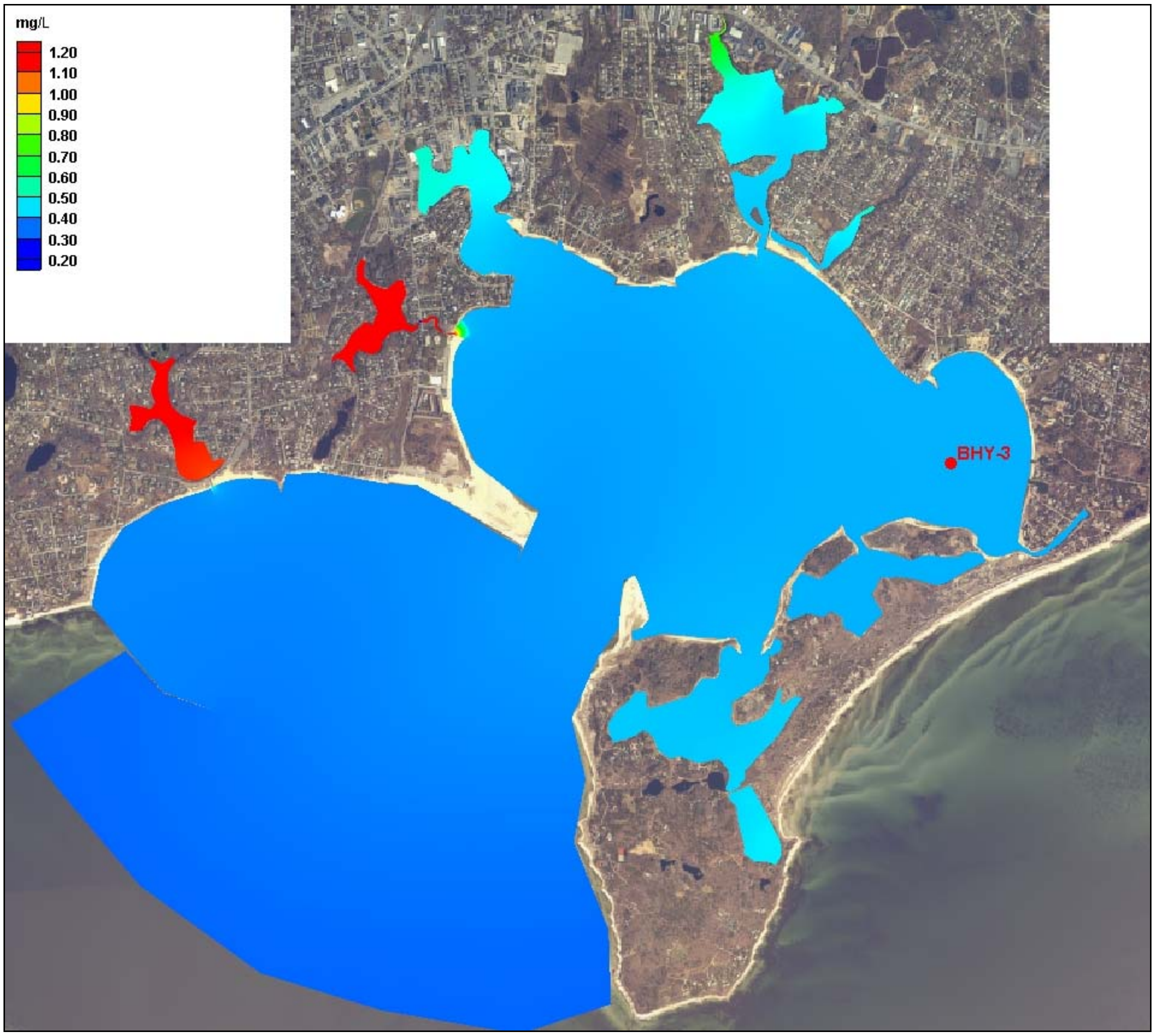


Figure VIII-1. Contour plot of modeled average total nitrogen concentrations (mg/L) in the Lewis Bay system, for threshold conditions (0.38 mg/L at water quality monitoring station BHY-3, and less than 0.5 at water quality monitoring station MC-1 and the average of stations BH-1 and BH-2). The approximate location of the sentinel threshold station for Lewis Bay (BHY-3) is shown.

Halls Creek Estuary: All of the key habitat indicators are consistent within the Halls Creek Estuary, and particularly its tidal creeks, supporting high quality habitat in line with the salt marsh structure and function of this system (Chapter VII). Given that Halls Creek does not appear to be a system structured to support eelgrass habitat, its nitrogen threshold needs to focus on infaunal animal communities. Overall, the infauna survey described in Chapter VII indicated that most areas within the creeks and basin of the Halls Creek Estuary are supporting infauna habitat typical of organic rich New England salt marshes, hence high quality relative to this estuarine ecosystem type. This is supported by the absence of macroalgal accumulations and algal mats within the creek bottoms which can result if there is "excessive" external nitrogen loading. The absence of macroalgal accumulations is consistent with the low total nitrogen levels within this system, 0.385-0.469 mg N L^{-1} (tidally averaged). This is in comparison to a similar marsh, Cockle Cove Creek (Chatham), which supports high quality habitats, both emergent marsh and creek bottom, at levels of 2 mg N L^{-1}. Based upon all lines of evidence it appears that the Halls Creek Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment.

A principal component of the high tolerance of salt marsh systems to nitrogen inputs from groundwater and surface water inflows is that unlike embayments, creek waters cannot accumulate nutrients over multiple tidal cycles as embayments do. In addition, increasing the nitrogen concentration in the tidal waters that flood the marsh plain will have a negligible or possibly a stimulatory effect on marsh primary and likely secondary production (i.e. an enhancement of habitat). In addition, since the inflowing fresh waters flow down gradient through the marsh creek and out to the Centerville Harbor and Nantucket Sound, the nitrogen level in estuarine waters will never exceed the inflowing freshwater nitrogen level. As was the case for the Cockle Cove Creek system (similar in structure to the Halls Creek system), it was determined that a highly conservative nitrogen threshold would yield a total nitrogen level of <2 mg N L^{-1} throughout the salt marsh (e.g. from headwaters to tidal inlet). As this system closely resembles the structure and hydrodynamics of Halls Creek, this threshold level appears to be appropriate for Halls Creek marsh as well. It should be noted that the upper most marsh reach of Cockle Cove is currently exposed to 2-3 mg N L^{-1} without discernable habitat impairment. Also, it is important to note that since the creek bottom sediments remove nitrate during transport, the TN concentration declines along the tidal reach. As such, the lower tidal reach has a significantly lower tidally averaged concentration compared to the headwaters. This can be seen in the existing TN gradient, where the tidally averaged TN concentration in Halls Creek is 0.469 mg N L^{-1} and 0.385 mg N L^{-1} at the inlet.

Putting all the assessment elements together, it appears that for Halls Creek, the critical values are a total nitrogen level of 2 mg N L^{-1} in the headwaters (Station BC-13) and a level of 1 mg N L^{-1} at the border of the upper and lower reach (Station BC-14). As this upper/lower boundary station is the uppermost long-term marine water quality sampling site and integrates all of the watershed and upper marsh nitrogen inputs and removals, it was selected as the sentinel station for this system (BC-14). The threshold (tidally averaged) total nitrogen level of 1 mg N L^{-1} was determined to be appropriate for the sentinel station (BC-14). It should be noted that the tidally averaged total nitrogen level at the middle marsh station in Cockle Cove Creek is currently 1.378 mg N L^{-1} and the tidal inlet station shows concentrations of 0.472 mg N L^{-1}, consistent with the 1 mg N L^{-1} at the sentinel station in Halls Creek. This threshold applies as long as the tidal creek maintains its present hydrodynamic characteristics (flushing and velocity). The nitrogen threshold for Halls Creek salt marsh is intentionally conservative based upon all available data from comparable systems. However, it indicates that additional nitrogen may enter this system without impairment of its habitat quality throughout the estuary. The nitrogen loads associated with the threshold concentration at the sentinel location are discussed in Section VIII.3, below. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-2.

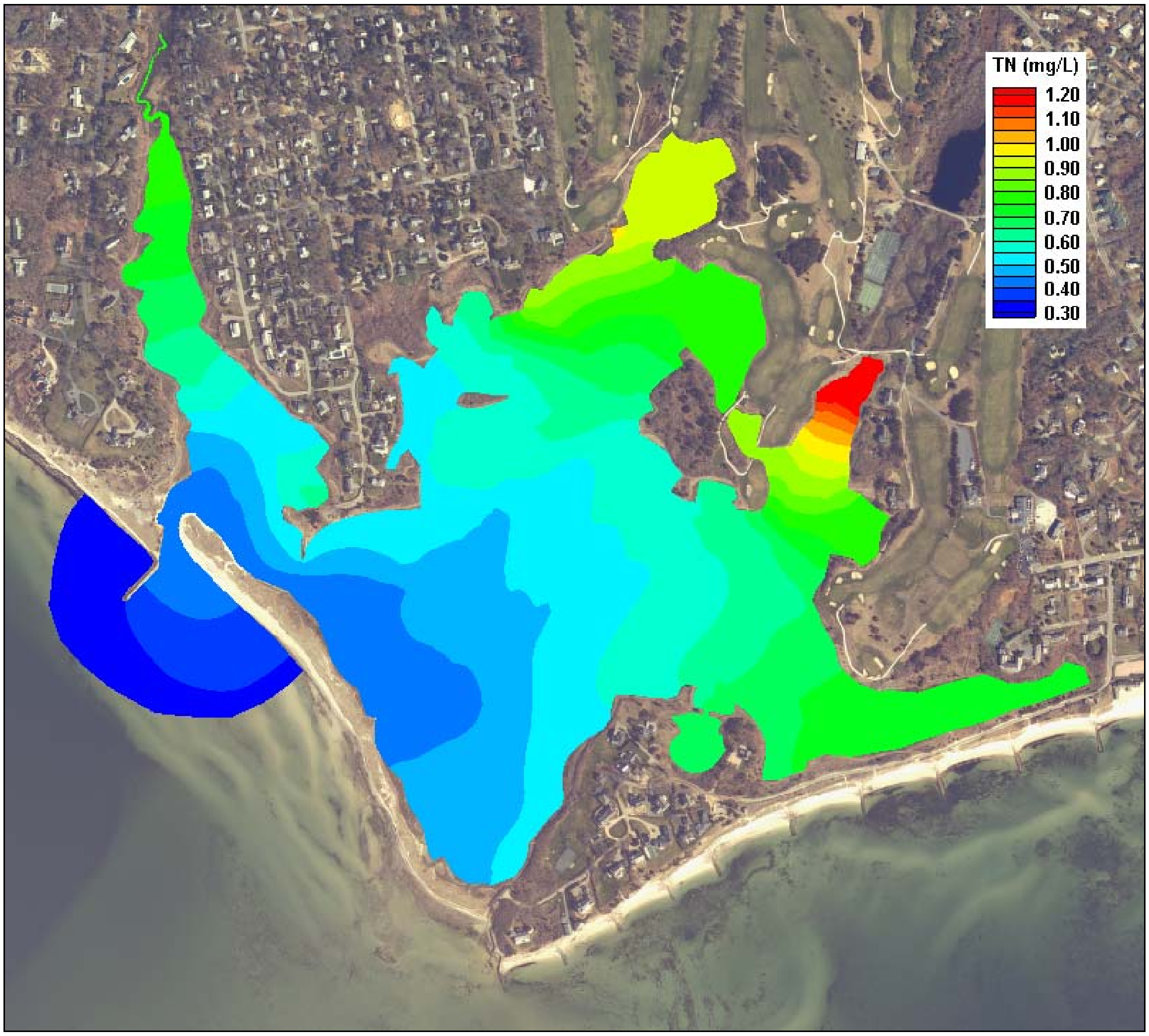


Figure VIII-2. Contour plot of tidally averaged modeled total nitrogen concentrations (mg/L) in the Halls Creek system, for threshold conditions (maximum concentration of 2.0 mg/L at monitoring station BC-13 and 1.0 mg/L at BC-14).

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Lewis Bay Embayment System and the level of additional nitrogen loading to Halls Creek which will still sustain high quality habitat in that 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.

It should be noted, one approach to achieving the nitrogen load reductions within the Lewis Bay Embayment System necessary to achieve the threshold nitrogen concentrations built upon the "Existing Removal Scenario B", presented to the MEP Technical Team by the Towns of Yarmouth and Barnstable and described in Chapter IX. Since this version of Scenario B did not achieve the threshold targets (Chapter IX), additional removal of septic N loading was necessary. The threshold nitrogen level at the sentinel station and at the secondary stations was achieved when removal of septic N loading was increased to produce an 80% total reduction in loading from this source to the main basin of Lewis Bay (Watershed 16) and an 80% reduction from this source to Hyannis Inner Harbor (Watershed 13). The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

Lewis Bay Estuary: Watershed nitrogen loads to Lewis Bay 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 Lewis Bay Embayment System (BHY-3 located in the eastern basin of Lewis Bay), and at the secondary stations in Uncle Roberts Cove, Hyannis Inner Harbor and Mill Creek. 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.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required using: 1) Existing Removal Scenario B (as requested by the Towns of Yarmouth and Barnstable) with 2) additional removal of septic N loading to produce an 80% total reduction in loading from this source to the main basin of Lewis Bay (Watershed 16) and 3) an 80% reduction from septic N Loading to Hyannis Inner Harbor (Watershed 13). 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 Lewis Bay 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
Lewis Bay	26.490	5.299	-80.0%
Uncle Roberts Cove	0.214	0.214	0.0%
Mill Creek	13.570	1.926	-85.8%
Hyannis Inner Harbor	6.847	1.808	-73.6%[1]
Snows Creek	7.970	9.088	+14.0%
Stewarts Creek	21.564	24.178	+12.1%
Surface Water Sources			
Chase Brook	2.488	2.479	-0.3%
Mill Pond	10.425	10.068	-3.4%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

[1] Hyannis Inner Harbor is a combination of Hyannis Inner Harbor watershed (13), and Wells Mary Dunn watershed (6) thus the 80% reduction in septic loading for the threshold does not result in a direct 80% reduction in septic loading.

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. Removal of septic loads from Existing

Removal Scenario B along with the additional septic removals from Lewis Bay and Hyannis Inner Harbor 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. The benthic flux for this modeling effort is reduced from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Nantucket Sound.

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Lewis Bay	30.855	9.663	-68.7%
Uncle Roberts Cove	0.540	0.540	0.0%
Mill Creek	15.964	4.321	-72.9%
Hyannis Inner Harbor	12.153	7.115	-41.5%
Snows Creek	15.115	16.233	+7.4%
Stewarts Creek	38.992	41.605	+6.7%
Surface Water Sources			
Chase Brook	3.345	3.337	-0.2%
Mill Pond	15.038	14.682	-2.4%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

Table VIII-4. Threshold sub-embayment loads and attenuated surface water loads used for total nitrogen modeling of the Lewis Bay 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)
Lewis Bay	9.663	13.507	23.916
Uncle Roberts Cove	0.540	0.759	10.991
Mill Creek	4.321	0.627	-1.208
Hyannis Inner Harbor	7.115	0.633	9.780
Snows Creek	16.233	-	-4.533
Stewarts Creek	41.605	0.236	-10.402
Surface Water Sources			
Chase Brook	3.337	-	-
Mill Pond	14.682	-	-
Hospital Creek/Hyannis Inner	0.326	-	-

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, a reduction in TN concentration of approximately 7% is required at station BHY-3. To meet the secondary threshold requirement for stations BHY-4 (Uncle Roberts Cove), MC-1 (Mill Creek) and the average of BH-1 and BH-2 (Hyannis Inner Harbor), a reduction in TN concentration of approximately 7.0%, 13% and 12% were required, respectively.

The basis for the watershed nitrogen removal strategy utilized to achieve the embayment thresholds may have merit, since this example nitrogen remediation effort is focused on watersheds where groundwater is flowing directly into the estuary. For nutrient loads entering the systems through surface flow, natural attenuation in freshwater bodies (i.e., streams and ponds) can significantly reduce the load that finally reaches the estuary. Presently, this attenuation is occurring due to natural ecosystem processes and the extent of attenuation being determined by the mass of nitrogen which discharges to these systems. The nitrogen reaching these systems is currently "unplanned", resulting primarily from the widely distributed non-point nitrogen sources (e.g. septic systems, lawns, etc.). Future nitrogen management should take advantage of natural nitrogen attenuation, where possible, to ensure the most cost-effective nitrogen reduction strategies. However, "planned" use of natural systems has to be done carefully and with the full analysis to ensure that degradation of these systems will not occur. One clear finding of the MEP has been the need for analysis of the potential associated with restored wetlands or ecologically engineered ponds/wetlands to enhance nitrogen attenuation. Attenuation by ponds in agricultural systems has also been found to work in some cranberry bog systems, as well. Cranberry bogs, other freshwater wetland resources, and freshwater ponds provide opportunities for enhancing natural attenuation of their nitrogen loads. Restoration or enhancement of wetlands and ponds associated with the lower ends of rivers and/or streams discharging to estuaries are seen as providing a dual service of lowering infrastructure costs associated with wastewater management and increasing aquatic resources associated within the watershed and upper estuarine reaches.

Table VIII-5. Comparison of model average total N concentrations from present loading and the modeled threshold scenario, with percent change, for the Lewis Bay system. Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.477**	**-13.1%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.440**	**-11.4%**
Hyannis Inner Harbor	BH-3	0.440	0.400	-9.0%
Snows Creek	BH-4	1.638	1.745	+6.6%
Lewis Bay	BH-5	0.387	0.365	-5.5%
Lewis Bay	BH-6	0.368	0.353	-4.2%
Stuarts Creek	BH-7	1.374	1.435	+4.4%
Lewis Bay	BHY-1	0.384	0.364	-5.3%
Lewis Bay	BHY-2	0.414	0.383	-7.5%
Lewis Bay	**BHY-3**	**0.407**	**0.378**	**-7.2%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.400**	**-7.0%**
Mill Creek	**MC-1**	**0.531**	**0.462**	**-13.0%**
Mill Creek	MC-2	0.473	0.421	-11.0%

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.

Halls Creek Estuary: 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 Halls Creek system. Total nitrogen thresholds derived in Section VIII.1 and VIII.2 were used to adjust the calibrated constituent transport model developed in Section VI. Contrary to most other estuarine systems evaluated as part MEP, the threshold concentration was set higher than present conditions, meaning that the system would be allowed to have a higher load than present to meat the threshold. Therefore, watershed nitrogen loads were sequentially raised in the model until the nitrogen levels either reached the 1.0 mg/L threshold level at the sentinel station (BC-14) chosen for Halls Creek, or reached a tidally averaged maximum of 2.00 mg/L at the headwaters of the system. It is important to note that load increases could be produced by increasing any or all sources of nitrogen to the system. The load increases presented below represent only one of a suite of potential approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of loading that will be allowable for this system. A comparison between present watershed loading and the loadings for the modeled threshold scenario is provided in Tables VIII-6, 7 and 8.

As shown in Table VIII-6, the threshold scenario run for this system would allow up to 1.57 times (57% increase) the present watershed loading. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-2.

Table VIII-7 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-7, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent ‘worst-case’ summertime conditions. The benthic flux for this modeling effort is modified from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Nantucket Sound, as discussed in Section VI.2.6.1.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-8. To achieve the threshold nitrogen concentrations at the sentinel station, increases in average TN concentrations of typically greater than 19% occur in the system, between the main harbor basin and the marsh.

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

Table VIII-6. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Halls Creek system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Halls Creek	21.534	32.918	+52.9%
Halls Creek Stream (freshwater)	1.597	3.345	+109.4%
System Total	23.132	36.263	+56.8%

Table VIII-7. Threshold sub-embayment loads used for total nitrogen modeling of the Halls Creek 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)
Halls marsh	32.918	0.630	6.649
Halls Creek (freshwater)	3.345	-	-
System Total	36.263	0.630	6.649

Table VIII-8. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the Halls Creek system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Halls Creek - stream	BC-13	1.189	2.037	+71.4%
Halls Creek - mid	**BC-14**	**0.469**	**0.557**	**+18.9%**
Halls Creek - inlet	BC-15	0.385	0.432	+12.1%

IX. ALTERNATIVES TO IMPROVE WATER QUALITY

At the request of Town of Barnstable and Town of Yarmouth staff, MEP staff completed six additional scenarios in July of 2007. Through a current Comprehensive Wastewater Management Planning process, the Town of Yarmouth delineated a potential sewer district (Section IV, Figure IV-6). Both town staffs agreed to the following scenarios: A) collection of wastewater within the proposed district and removal of wastewater loads from Lewis Bay watershed, B) collection of wastewater within the proposed district and treatment and discharge at the Hyannis WPCF, and C) collection of wastewater within the proposed district, treatment at the Hyannis WPCF, and discharge within an abandoned bog system to the east of Cape Cod Hospital. Wastewater flows were developed under both current and buildout conditions. It should be noted that in subsequent 18-months since the original six scenarios were run, the water quality models have been further developed and improved upon, thus there may be slight changes in the base loading for the watersheds. However, since these scenarios did not meet the threshold requirements, they were not revisited.

MEP staff developed a separate “sewershed” module for the proposed district, which cuts across six sub-watersheds. The sewershed module contains all the properties in the proposed district according to their current sub-watershed assignments. Just as in the standard nitrogen loading analysis, staff determined water use for all developed properties within the sewershed and potential future water use at buildout based on a review of developable land and additional development on existing developed properties. Total existing wastewater load within the whole sewershed is 7,792 kg/yr and buildout will add 2,486 kg/yr.

Under scenario A, the existing and buildout loads from the sewershed are removed from the respective sub-watersheds. Under scenario B, wastewater flows are assumed to be discharged at the Hyannis WPCF and redistributed to various sub-watersheds based on the analyses described above. Under scenario C, the WPCF-treated effluent from the sewershed is discharged at the abandoned bogs in the Inner Harbor Creek sub-watershed. The scenario C loads receive an additional 30% attenuation from the bog system. Overall impacts on all loads are shown in Table IV-5.

Six additional scenarios were provided to the MEP in the Fall of 2008, by Town of Barnstable and Town of Yarmouth staff. The new scenarios evolved out of the water quality results from the original six scenarios (A through C). Both town staffs agreed to the following scenarios: D) collection of wastewater within the proposed district and removal of wastewater loads from Lewis Bay watershed and discharge outside the watershed, E) collection of wastewater within the proposed district and treatment and discharge at the Hyannis WPCF, and F) collection of wastewater within the proposed district, treatment at the Hyannis WPCF, and discharge within an abandoned bog system to the east of Cape Cod Hospital. Wastewater flows were developed under both current and buildout conditions.

Under scenario D, the existing and buildout loads from the sewershed are removed from the respective sub-watersheds. Under scenario E, wastewater flows are assumed to be discharged at the Hyannis WPCF and redistributed to various sub-watersheds based on the analyses described above. Under scenario F, the WPCF-treated effluent from the sewershed is discharged at the abandoned bogs in the Inner Harbor Creek sub-watershed. The scenario F loads receive an additional 30% attenuation from the bog system.

IX.1 EXISTING LOADING SCENARIO A

Based on the potential sewer district developed by the Town of Yarmouth under their ongoing CWMP process, a set of scenarios were developed to be modeled by the MEP. Both the Towns of Barnstable and Yarmouth were in agreement about the types of scenarios to be modeled and worked together to develop them. Scenario A as developed jointly by the two Towns is based on collection of wastewater within the proposed district and removal of wastewater loads from Lewis Bay watershed. Wastewater flows were developed under both current as presented herein and buildout conditions provided below (Section IX.4). Table IX-1 and Table IX-2 illustrate the overall change to septic and watershed loads resulting from this alternative. Septic removal from potential Lewis Bay sewer district results in significant reductions in the watershed loads in specific sub-embayments, particularly the Mill Creek and Hyannis Inner Harbor sub-watersheds. Based on the assumptions developed for this alternative, Table IX-3 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is approached (0.391 mg/L TN at BHY-3) but not reached at the sentinel station. The load reduction associated with this scenario did yield water column concentrations that were <0.5 mg/L TN (infaunal threshold) at 2 of 3 locations selected as check stations. Concentrations at MC-1 and BH-2 were 0.472 mg/L and 0.486 mg/L respectively, slightly less than the 0.5 mg/L infaunal target.

Table IX-1. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Existing Scenario A. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	21.647	-18.3%
Uncle Roberts Cove	0.214	0.214	+0.0%
Mill Creek	13.570	1.923	-85.8%
Hyannis Inner Harbor	6.847	4.663	-31.9%
Snows Creek	7.970	7.970	+0.0%
Stewarts Creek	21.564	21.564	+0.0%
Surface Water Sources			
Chase Brook	2.488	2.463	-1.0%
Mill Pond	10.425	10.003	-4.0%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

Table IX-2. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario A. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.			
sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	26.011	-15.7%
Uncle Roberts Cove	0.540	0.540	+0.0%
Mill Creek	15.964	4.318	-73.0%
Hyannis Inner Harbor	12.153	9.970	-18.0%
Snows Creek	15.115	15.115	+0.0%
Stewarts Creek	38.992	38.992	+0.0%
Surface Water Sources			
Chase Brook	3.345	3.321	-0.7%
Mill Pond	15.038	14.616	-2.8%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

Table IX-3. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario A, with total watershed N loads, atmospheric N loads, and benthic flux.			
sub-embayment	scenario load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Lewis Bay	26.011	13.507	24.872
Uncle Roberts Cove	0.540	0.759	11.940
Mill Creek	4.318	0.627	-1.208
Hyannis Inner Harbor	9.970	0.633	18.990
Snows Creek	15.115	-	-4.533
Stewarts Creek	38.992	0.236	-9.683
Surface Water Sources			
Chase Brook	3.321	-	-
Mill Pond	14.616	-	-
Hospital Creek/Hyannis Inner	0.326	-	-

Table IX-4. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario A), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.535**	**-2.5%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.486**	**-2.0%**
Hyannis Inner Harbor	BH-3	0.440	0.422	-4.1%
Snows Creek	BH-4	1.638	1.626	-0.7%
Lewis Bay	BH-5	0.387	0.375	-3.1%
Lewis Bay	BH-6	0.368	0.359	-2.4%
Stewarts Creek	BH-7	1.374	1.372	-0.1%
Lewis Bay	BHY-1	0.384	0.372	-3.0%
Lewis Bay	BHY-2	0.414	0.394	-4.8%
Lewis Bay	**BHY-3**	**0.407**	**0.391**	**-4.0%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.414**	**-3.9%**
Mill Creek	**MC-1**	**0.531**	**0.472**	**-11.1%**
Mill Creek	MC-2	0.473	0.433	-8.6%

IX.2 EXISTING LOADING SCENARIO B

Scenario B as developed jointly by the two Towns is based on collection of wastewater within the proposed district and treatment and discharge at the Hyannis WPCF. Wastewater flows were developed under both current conditions presented herein and buildout conditions provided below (Section IX.5). Table IX-5 and Table IX-6 illustrate the overall change to septic and watershed loads resulting from this alternative. Septic removal from potential Lewis Bay sewer district results in significant reductions in the watershed loads in specific sub-embayments, particularly the Mill Creek and Hyannis Inner Harbor sub-watersheds. Unlike Scenario A that showed no change in the septic loads (present vs. scenario) for the Snows Creek and Stewarts Creek sub-watershed, under Scenario B septic loads increase in Snows Creek and decrease in Stewarts Creek. Based on the assumptions developed for this alternative, Table IX-7 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is approached (0.391 mg/L TN at BHY-3) but not reached at the sentinel station. The load reduction associated with this scenario did yield water column concentrations that were <0.5 mg/L TN (infaunal threshold) at 2 of 3 locations selected as check stations. Concentrations at MC-1 and BH-2 were 0.472 mg/L and 0.488 mg/L respectively, slightly less than the 0.5 mg/L infaunal target.

Table IX-5. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Existing Scenario B. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	21.647	-18.3%
Uncle Roberts Cove	0.214	0.214	0.0%
Mill Creek	13.570	1.923	-85.8%
Hyannis Inner Harbor	6.847	4.899	-28.5%
Snows Creek	7.970	9.088	+14.0%
Stewarts Creek	21.564	13.775	-36.1%
Surface Water Sources			
Chase Brook	2.488	2.463	-1.0%
Mill Pond	10.425	10.003	-4.0%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

Table IX-6. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario B. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	26.011	-15.7%
Uncle Roberts Cove	0.540	0.540	0.0%
Mill Creek	15.964	4.318	-73.0%
Hyannis Inner Harbor	12.153	10.205	-16.0%
Snows Creek	15.115	16.233	+7.4%
Stewarts Creek	38.992	31.203	-20.0%
Surface Water Sources			
Chase Brook	3.345	3.321	-0.7%
Mill Pond	15.038	14.616	-2.8%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

Table IX-7. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario B, 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)
Lewis Bay	26.011	13.507	25.067
Uncle Roberts Cove	0.540	0.759	11.980
Mill Creek	4.318	0.627	-1.208
Hyannis Inner Harbor	10.205	0.633	19.173
Snows Creek	16.233	-	-4.533
Stewarts Creek	31.233	0.236	-10.402
Surface Water Sources			
Chase Brook	3.321	-	-
Mill Pond	14.616	-	-
Hospital Creek/Hyannis Inner	0.326	-	-

Table IX-8. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario B), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.538**	**-2.1%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.488**	**-1.7%**
Hyannis Inner Harbor	BH-3	0.440	0.422	-3.9%
Snows Creek	BH-4	1.638	1.754	+7.1%
Lewis Bay	BH-5	0.387	0.375	-3.1%
Lewis Bay	BH-6	0.368	0.359	-2.5%
Stewarts Creek	BH-7	1.374	1.074	-21.9%
Lewis Bay	BHY-1	0.384	0.372	-3.1%
Lewis Bay	BHY-2	0.414	0.394	-4.9%
Lewis Bay	**BHY-3**	**0.407**	**0.391**	**-4.1%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.414**	**-4.0%**
Mill Creek	**MC-1**	**0.531**	**0.472**	**-11.2%**
Mill Creek	MC-2	0.473	0.432	-8.7%

IX.3 EXISTING LOADING SCENARIO C

Scenario C as developed jointly by the two Towns is based on Collection of wastewater within the proposed district, treatment at the Hyannis WPCF, and discharge within an abandoned bog system to the east of Cape Cod Hospital. Wastewater flows were developed under both current conditions presented herein and buildout conditions provided below (Section IX.6). Table IX-9 and Table IX-10 illustrate the overall change to septic and watershed loads resulting from this alternative. Septic removal from potential Lewis Bay sewer district results in significant reductions in the watershed loads in specific sub-embayments, particularly the Mill Creek and Hyannis Inner Harbor sub-watersheds. Unlike Scenario B that showed change in the septic loads (present vs. scenario) for the Snows Creek and Stewarts Creek sub-watershed, under Scenario C septic loads did not change from present conditions for both Snows Creek and Stewarts Creek (similar to Scenario A results). As would be expected, loads to Hospital Creek/Hyannis Inner Harbor go up dramatically over present conditions. Based on the assumptions developed for this alternative, Table IX-11 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is approached less so than under Scenario A and B (0.399 mg/L TN at BHY-3) but not reached at the sentinel station. The load reduction associated with this scenario did yield water column concentrations that were <0.5 mg/L TN (infaunal threshold) at 1 of 3 locations selected as check stations. Concentrations at MC-1 was 0.480 mg/L, slightly less than the 0.5 mg/L infaunal target but not as low as under Scenario A and B.

Table IX-9. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Existing Scenario C. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	21.647	-18.3%
Uncle Roberts Cove	0.214	0.214	+0.0%
Mill Creek	13.570	1.923	-85.8%
Hyannis Inner Harbor	6.847	4.663	-31.9%
Snows Creek	7.970	7.970	0.0%
Stewarts Creek	21.564	21.564	0.0%
Surface Water Sources			
Chase Brook	2.488	2.463	-1.0%
Mill Pond	10.425	10.003	-4.0%
Hospital Creek/Hyannis Inner	1.907	3.753	+96.8%

Table IX-10. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario C. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	26.011	-15.7%
Uncle Roberts Cove	0.540	0.540	0.0%
Mill Creek	15.964	4.318	-73.0%
Hyannis Inner Harbor	12.153	9.970	-18.0%
Snows Creek	15.115	15.115	0.0%
Stewarts Creek	38.992	38.992	0.0%
Surface Water Sources			
Chase Brook	3.345	3.321	-0.7%
Mill Pond	15.038	14.616	-2.8%
Hospital Creek/Hyannis Inner	1.907	3.753	+96.8%

Table IX-11. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario C, 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)
Lewis Bay	26.011	13.507	25.176
Uncle Roberts Cove	0.540	0.759	12.098
Mill Creek	4.318	0.627	-1.208
Hyannis Inner Harbor	9.970	0.633	18.990
Snows Creek	15.115	-	-4.533
Stewarts Creek	38.992	0.236	-9.683
Surface Water Sources			
Chase Brook	3.321	-	-
Mill Pond	14.616	-	-
Hospital Creek/Hyannis Inner	3.753	-	-

Table IX-12. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario C), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.

Sub-Embayment	monitorin g station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.552**	**+0.5%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.503**	**+1.5%**
Hyannis Inner Harbor	BH-3	0.440	0.438	-0.3%
Snows Creek	BH-4	1.638	1.635	-0.2%
Lewis Bay	BH-5	0.387	0.384	-0.8%
Lewis Bay	BH-6	0.368	0.365	-0.9%
Stewarts Creek	BH-7	1.374	1.375	+0.1%
Lewis Bay	BHY-1	0.384	0.379	-1.2%
Lewis Bay	BHY-2	0.414	0.403	-2.8%
Lewis Bay	**BHY-3**	**0.407**	**0.399**	**-2.0%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.422**	**-2.1%**
Mill Creek	**MC-1**	**0.531**	**0.480**	**-9.7%**
Mill Creek	MC-2	0.473	0.441	-6.9%

IX.4 BUILD-OUT LOADING SCENARIO A

Scenario A (buildout) as developed jointly by the two Towns is based on collection of wastewater within the proposed district and removal of wastewater loads from Lewis Bay watershed. Wastewater flows were developed under both current conditions as presented above (Section IX.1) and buildout conditions herein. Table IX-13 and Table IX-14 illustrate the overall change to septic and watershed loads resulting from this alternative. Based on the assumptions developed for this alternative, Table IX-15 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is exceeded at the sentinel station and infaunal check stations under build out conditions.

Table IX-13. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Build-Out Scenario A. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	20.603	-22.2%
Uncle Roberts Cove	0.214	0.340	+59.0%
Mill Creek	13.570	-2.775	-120.5%
Hyannis Inner Harbor	6.847	4.616	-32.6%
Snows Creek	7.970	9.893	+24.1%
Stewarts Creek	21.564	25.307	+17.4%
Surface Water Sources			
Chase Brook	2.488	2.318	-6.8%
Mill Pond	10.425	8.986	-13.8%
Hospital Creek/Hyannis Inner	1.907	0.332	-82.6%

Table IX-14. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario A. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	29.049	-5.9%
Uncle Roberts Cove	0.540	0.715	+32.5%
Mill Creek	15.964	5.721	-64.2%
Hyannis Inner Harbor	12.153	12.690	+4.4%
Snows Creek	15.115	21.529	+42.4%
Stewarts Creek	38.992	53.959	+38.4%
Surface Water Sources			
Chase Brook	3.345	3.896	+16.5%
Mill Pond	15.038	21.074	+40.1%
Hospital Creek/Hyannis Inner	1.907	0.332	-82.6%

Table IX-15. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario A, 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)
Lewis Bay	29.049	13.507	26.482
Uncle Roberts Cove	0.715	0.759	13.008
Mill Creek	5.721	0.627	-1.437
Hyannis Inner Harbor	12.690	0.633	21.238
Snows Creek	21.529	-	-6.458
Stewarts Creek	53.959	0.236	-13.489
Surface Water Sources			
Chase Brook	3.896	-	-
Mill Pond	21.074	-	-
Hospital Creek/Hyannis Inner	0.332	-	-

Table IX-16. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario A), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.575**	**+4.6%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.518**	**+4.3%**
Hyannis Inner Harbor	BH-3	0.440	0.442	+0.5%
Snows Creek	BH-4	1.638	2.171	+32.6%
Lewis Bay	BH-5	0.387	0.387	+0.1%
Lewis Bay	BH-6	0.368	0.368	+0.1%
Stewarts Creek	BH-7	1.374	1.767	+28.6%
Lewis Bay	BHY-1	0.384	0.384	-0.1%
Lewis Bay	BHY-2	0.414	0.412	-0.4%
Lewis Bay	**BHY-3**	**0.407**	**0.406**	**-0.3%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.430**	**-0.2%**
Mill Creek	**MC-1**	**0.531**	**0.538**	**+1.2%**
Mill Creek	MC-2	0.473	0.468	-1.2%

IX.5 BUILD-OUT LOADING SCENARIO B

Scenario B (buildout) as developed jointly by the two Towns is based on collection of wastewater within the proposed district and treatment and discharge at the Hyannis WPCF. Wastewater flows were developed under both current conditions as presented above (Section IX.2) and buildout conditions herein. Table IX-17 and Table IX-18 illustrate the overall change to septic and watershed loads resulting from this alternative. Based on the assumptions developed for this alternative, Table IX-19 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is exceeded at the sentinel station and infaunal check stations under build out conditions.

Table IX-17. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Build-Out Scenario B. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	20.603	-22.2%
Uncle Roberts Cove	0.214	0.340	+59.0%
Mill Creek	13.570	-2.775	-120.5%
Hyannis Inner Harbor	6.847	4.904	-28.4%
Snows Creek	7.970	11.255	+41.2%
Stewarts Creek	21.564	14.203	-34.1%
Surface Water Sources			
Chase Brook	2.488	2.318	-6.8%
Mill Pond	10.425	8.986	-13.8%
Hospital Creek/Hyannis Inner	1.907	0.332	-82.6%

Table IX-18. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario B. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	29.049	-5.9%
Uncle Roberts Cove	0.540	0.715	+32.5%
Mill Creek	15.964	5.721	-64.2%
Hyannis Inner Harbor	12.153	12.978	+6.8%
Snows Creek	15.115	22.890	+51.4%
Stewarts Creek	38.992	42.855	+9.9%
Surface Water Sources			
Chase Brook	3.345	3.896	+16.5%
Mill Pond	15.038	21.074	+40.1%
Hospital Creek/Hyannis Inner	1.907	0.332	-82.6%

Table IX -19. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario B, 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)
Lewis Bay	29.049	13.507	26.326
Uncle Roberts Cove	0.715	0.759	13.087
Mill Creek	5.721	0.627	-1.437
Hyannis Inner Harbor	12.978	0.633	21.463
Snows Creek	22.890	-	-6.458
Stewarts Creek	42.855	0.236	-14.288
Surface Water Sources			
Chase Brook	3.896	-	-
Mill Pond	21.074	-	-
Hospital Creek/Hyannis Inner	0.332	-	-

Table IX-20. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario B), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.577**	**+5.0%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.519**	**+4.6%**
Hyannis Inner Harbor	BH-3	0.440	0.442	+0.6%
Snows Creek	BH-4	1.638	2.325	+42.0%
Lewis Bay	BH-5	0.387	0.386	-0.1%
Lewis Bay	BH-6	0.368	0.367	-0.2%
Stewarts Creek	BH-7	1.374	1.349	-1.8%
Lewis Bay	BHY-1	0.384	0.383	-0.3%
Lewis Bay	BHY-2	0.414	0.411	-0.7%
Lewis Bay	**BHY-3**	**0.407**	**0.405**	**-0.6%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.429**	**-0.4%**
Mill Creek	**MC-1**	**0.531**	**0.537**	**+1.0%**
Mill Creek	MC-2	0.473	0.467	-1.4%

IX.6 BUILD-OUT LOADING SCENARIO C

Scenario C (buildout) as developed jointly by the two Towns is based on collection of wastewater within the proposed district, treatment at the Hyannis WPCF, and discharge within an abandoned bog system to the east of Cape Cod Hospital. Wastewater flows were developed under both current conditions as presented above (Section IX.3) and buildout conditions herein. Table IX-21 and Table IX-22 illustrate the overall change to septic and watershed loads resulting from this alternative. Based on the assumptions developed for this alternative, Table IX-23 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is exceeded at the sentinel station and infaunal check stations under build out conditions.

Table IX-21. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Build-Out Scenario C. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	20.603	-22.2%
Uncle Roberts Cove	0.214	0.340	+59.0%
Mill Creek	13.570	-2.775	-120.5%
Hyannis Inner Harbor	6.847	4.616	-32.6%
Snows Creek	7.970	9.896	+24.2%
Stewarts Creek	21.564	14.203	-34.1%
Surface Water Sources			
Chase Brook	2.488	2.318	-6.8%
Mill Pond	10.425	8.986	-13.8%
Hospital Creek/Hyannis Inner	1.907	4.507	+136.4%

Table IX-22. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario C. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	29.049	-5.9%
Uncle Roberts Cove	0.540	0.715	+32.5%
Mill Creek	15.964	5.721	-64.2%
Hyannis Inner Harbor	12.153	12.690	+4.4%
Snows Creek	15.115	21.532	+42.5%
Stewarts Creek	38.992	42.855	+9.9%
Surface Water Sources			
Chase Brook	3.345	3.896	+16.5%
Mill Pond	15.038	21.074	+40.1%
Hospital Creek/Hyannis Inner	1.907	4.507	+136.4%

Table IX-23. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario C, 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)
Lewis Bay	29.049	13.507	26.699
Uncle Roberts Cove	0.715	0.759	13.245
Mill Creek	5.721	0.627	-1.437
Hyannis Inner Harbor	12.690	0.633	21.238
Snows Creek	21.532	-	-6.458
Stewarts Creek	42.855	0.236	-14.288
Surface Water Sources			
Chase Brook	3.896	-	-
Mill Pond	21.074	-	-
Hospital Creek/Hyannis Inner	4.507	-	-

Table IX-24. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario C), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.594**	**+8.1%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.537**	**+8.2%**
Hyannis Inner Harbor	BH-3	0.440	0.461	+4.8%
Snows Creek	BH-4	1.638	2.181	+33.2%
Lewis Bay	BH-5	0.387	0.396	+2.5%
Lewis Bay	BH-6	0.368	0.373	+1.5%
Stewarts Creek	BH-7	1.374	1.352	-1.6%
Lewis Bay	BHY-1	0.384	0.391	+1.7%
Lewis Bay	BHY-2	0.414	0.421	+1.6%
Lewis Bay	**BHY-3**	**0.407**	**0.414**	**+1.6%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.438**	**+1.7%**
Mill Creek	**MC-1**	**0.531**	**0.545**	**+2.6%**
Mill Creek	MC-2	0.473	0.476	+0.6%

IX.7 EXISTING LOADING SCENARIO D

Based on the potential sewer district developed by the Town of Yarmouth under their ongoing CWMP process, a second set of six scenarios were developed to be modeled by the MEP. Scenario D as developed jointly by the two Towns is based on collection of wastewater within the proposed district and removal of wastewater loads from Lewis Bay watershed. Wastewater flows were developed under both current as presented herein and buildout conditions provided below (Section IX.10). Table IX-25 and Table IX-26 illustrate the overall change to septic and watershed loads resulting from this alternative. Septic removal from potential Lewis Bay sewer district results in significant reductions in the watershed loads in specific sub-embayments, particularly the Mill Creek and Hyannis Inner Harbor sub-watersheds. Based on the assumptions developed for this alternative, Table IX-27 presents the various components of nitrogen loading for the Lewis Bay system. The reductions in load related to the modeled sewer district, meet the threshold target (0.38 mg/L TN at BHY-3) at the sentinel station (0.373 mg/L TN at BHY-3). The load reduction associated with this scenario did yield water column concentrations that were <0.5 mg/L TN (infaunal threshold) at all 3 locations selected as check stations. Concentrations at MC-1 and BH-2 were 0.495 mg/L and 0.454 mg/L respectively, for an average concentration of 0.475 mg/L, which is below the 0.5 mg/L infaunal target. At stations BHY-4 and MC-1 concentrations were 0.396 mg/L and 0.449 mg/L respectively, which are below the 0.4 mg/L and 0.5 mg/L infaunal targets.

Table IX-25. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Existing Scenario D. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	0.351	-98.7%
Uncle Roberts Cove	0.214	0.214	0.0%
Mill Creek	13.570	1.614	-88.1%
Hyannis Inner Harbor	6.847	4.723	-31.0%
Snows Creek	7.970	7.970	0.0%
Stewarts Creek	21.564	21.564	0.0%
Surface Water Sources			
Chase Brook	2.488	1.077	-56.7%
Mill Pond	10.425	9.427	-9.6%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

Table IX-26. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario D. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	4.715	-84.7%
Uncle Roberts Cove	0.540	0.540	0.0%
Mill Creek	15.964	4.008	-74.9%
Hyannis Inner Harbor	12.153	10.030	-17.5%
Snows Creek	15.115	15.115	0.0%
Stewarts Creek	38.992	38.992	0.0%
Surface Water Sources			
Chase Brook	3.345	1.934	-42.2%
Mill Pond	15.038	14.041	-6.6%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

Table IX-27. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario D, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	scenario load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Lewis Bay	4.715	13.507	23.396
Uncle Roberts Cove	0.540	0.759	10.556
Mill Creek	4.008	0.627	-1.143
Hyannis Inner Harbor	10.030	0.633	11.261
Snows Creek	15.115	-	-4.533
Stewarts Creek	38.992	0.236	-9.750
Surface Water Sources			
Chase Brook	1.934	-	-
Mill Pond	14.041	-	-
Hospital Creek/Hyannis Inner	0.326	-	-

Table IX-28. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario D), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.495**	**-9.8%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.454**	**-8.5%**
Hyannis Inner Harbor	BH-3	0.440	0.405	-7.9%
Snows Creek	BH-4	1.638	1.615	-1.4%
Lewis Bay	BH-5	0.387	0.363	-6.1%
Lewis Bay	BH-6	0.368	0.350	-4.8%
Stewarts Creek	BH-7	1.374	1.365	-0.6%
Lewis Bay	BHY-1	0.384	0.361	-6.0%
Lewis Bay	BHY-2	0.414	0.378	-8.8%
Lewis Bay	**BHY-3**	**0.407**	**0.373**	**-8.4%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.396**	**-8.1%**
Mill Creek	**MC-1**	**0.531**	**0.449**	**-15.5%**
Mill Creek	MC-2	0.473	0.406	-14.3%

IX.8 EXISTING LOADING SCENARIO E

Scenario E as developed jointly by the two Towns is based on collection of wastewater within the proposed district and treatment and discharge at the Hyannis WPCF. Wastewater flows were developed under both current conditions presented herein and buildout conditions provided below (Section IX.11). Table IX-29 and Table IX-30 illustrate the overall change to septic and watershed loads resulting from this alternative. Septic removal from potential Lewis Bay sewer district results in significant reductions in the watershed loads in specific sub-embayments, particularly the Mill Creek and Hyannis Inner Harbor sub-watersheds. Unlike Scenario D that showed no change in the septic loads (present vs. scenario) for the Snows

Creek and Stewarts Creek sub-watershed, under Scenario E septic loads increase in Snows Creek and Stewarts Creek. Based on the assumptions developed for this alternative, Table IX-31 presents the various components of nitrogen loading for the Lewis Bay system. The reductions in load related to the modeled sewer district, meet the threshold target (0.38 mg/L TN at BHY-3) at the sentinel station (0.374 mg/L TN at BHY-3). In addition, the load reduction associated with this scenario did yield water column concentrations that were <0.5 mg/L TN (infaunal threshold) at all 3 locations selected as check stations. Concentrations at MC-1 and average of BH-1 and BH-2 were 0.450 mg/L and 0.480 mg/L respectively, slightly less than the 0.5 mg/L infaunal target.

Table IX-29. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Existing Scenario E. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	0.351	-98.7%
Uncle Roberts Cove	0.214	0.214	0.0%
Mill Creek	13.570	1.614	-88.1%
Hyannis Inner Harbor	6.847	5.244	-23.4%
Snows Creek	7.970	10.427	+30.8%
Stewarts Creek	21.564	27.310	+26.6%
Surface Water Sources			
Chase Brook	2.488	1.077	-56.7%
Mill Pond	10.425	9.427	-9.6%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

Table IX-30. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario E. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	4.715	-84.7%
Uncle Roberts Cove	0.540	0.540	0.0%
Mill Creek	15.964	4.008	-74.9%
Hyannis Inner Harbor	12.153	10.551	-13.2%
Snows Creek	15.115	17.573	+16.3%
Stewarts Creek	38.992	44.737	+14.7%
Surface Water Sources			
Chase Brook	3.345	1.934	-42.2%
Mill Pond	15.038	14.041	-6.6%
Hospital Creek/Hyannis Inner	1.907	0.326	-82.9%

Table IX-31. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario E, 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)
Lewis Bay	4.715	13.507	23.434
Uncle Roberts Cove	0.540	0.759	10.715
Mill Creek	4.008	0.627	-1.143
Hyannis Inner Harbor	10.551	0.633	11.538
Snows Creek	17.573	-	-5.272
Stewarts Creek	44.737	0.236	-11.188
Surface Water Sources			
Chase Brook	1.934	-	-
Mill Pond	14.041	-	-
Hospital Creek/Hyannis Inner	0.326	-	-

Table IX-32. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario E), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.502**	**-8.6%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.459**	**-7.5%**
Hyannis Inner Harbor	BH-3	0.440	0.408	-7.2%
Snows Creek	BH-4	1.638	1.821	+11.2%
Lewis Bay	BH-5	0.387	0.365	-5.6%
Lewis Bay	BH-6	0.368	0.352	-4.4%
Stewarts Creek	BH-7	1.374	1.516	+10.4%
Lewis Bay	BHY-1	0.384	0.362	-5.6%
Lewis Bay	BHY-2	0.414	0.379	-8.4%
Lewis Bay	**BHY-3**	**0.407**	**0.374**	**-8.0%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.398**	**-7.7%**
Mill Creek	**MC-1**	**0.531**	**0.450**	**-15.2%**
Mill Creek	MC-2	0.473	0.407	-13.9%

IX.9 EXISTING LOADING SCENARIO F

Scenario F as developed jointly by the two Towns is based on Collection of wastewater within the proposed district, treatment at the Hyannis WPCF, and discharge within an abandoned bog system to the east of Cape Cod Hospital. Wastewater flows were developed under both current conditions presented herein and buildout conditions provided below (Section IX.12). Table IX-33 and Table IX-34 illustrate the overall change to septic and watershed loads resulting from this alternative. Septic removal from potential Lewis Bay sewer district results in significant reductions in the watershed loads in specific sub-embayments, particularly the Mill Creek and Lewis Bay sub-watersheds. Unlike Scenario E that showed change in the septic loads (present vs. scenario) for the Snows Creek and Stewarts Creek sub-watershed, under

Scenario F septic loads did not change from present conditions for both Snows Creek and Stewarts Creek (similar to Scenario D results). As would be expected, loads to Hospital Creek/Hyannis Inner Harbor go up dramatically over present conditions. Based on the assumptions developed for this alternative, Table IX-35 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is approached (0.390 mg/L TN at BHY-3) but not reached at the sentinel station. The load reduction associated with this scenario did yield water column concentrations that were <0.5 mg/L TN (infaunal threshold) at 1 of 3 locations selected as check stations. Concentrations at MC-1 was 0.465 mg/L, slightly less than the 0.5 mg/L infaunal target.

Table IX-33. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Existing Scenario F. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	0.351	-98.7%
Uncle Roberts Cove	0.214	0.214	0.0%
Mill Creek	13.570	1.614	-88.1%
Hyannis Inner Harbor	6.847	4.723	-31.0%
Snows Creek	7.970	7.970	0.0%
Stewarts Creek	21.564	21.564	0.0%
Surface Water Sources			
Chase Brook	2.488	1.077	-56.7%
Mill Pond	10.425	9.427	-9.6%
Hospital Creek/Hyannis Inner	1.907	7.863	+312.4%

Table IX-34. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario F. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	4.715	-84.7%
Uncle Roberts Cove	0.540	0.540	0.0%
Mill Creek	15.964	4.008	-74.9%
Hyannis Inner Harbor	12.153	10.030	-17.5%
Snows Creek	15.115	15.115	0.0%
Stewarts Creek	38.992	38.992	0.0%
Surface Water Sources			
Chase Brook	3.345	1.934	-42.2%
Mill Pond	15.038	14.041	-6.6%
Hospital Creek/Hyannis Inner	1.907	7.863	+312.4%

Table IX-35. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario F, 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)
Lewis Bay	4.715	13.507	23.652
Uncle Roberts Cove	0.540	0.759	10.912
Mill Creek	4.008	0.627	-1.143
Hyannis Inner Harbor	10.030	0.633	11.261
Snows Creek	15.115	-	-4.533
Stewarts Creek	38.992	0.236	-9.750
Surface Water Sources			
Chase Brook	1.934	-	-
Mill Pond	14.041	-	-
Hospital Creek/Hyannis Inner	7.863	-	-

Table IX-36. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario F), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.532**	**-3.1%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.491**	**-1.1%**
Hyannis Inner Harbor	BH-3	0.440	0.441	+0.4%
Snows Creek	BH-4	1.638	1.634	-0.2%
Lewis Bay	BH-5	0.387	0.383	-1.0%
Lewis Bay	BH-6	0.368	0.362	-1.6%
Stewarts Creek	BH-7	1.374	1.371	-0.2%
Lewis Bay	BHY-1	0.384	0.376	-2.1%
Lewis Bay	BHY-2	0.414	0.396	-4.5%
Lewis Bay	**BHY-3**	**0.407**	**0.390**	**-4.2%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.413**	**-4.2%**
Mill Creek	**MC-1**	**0.531**	**0.465**	**-12.5%**
Mill Creek	MC-2	0.473	0.423	-10.6%

IX.10 BUILD-OUT LOADING SCENARIO D

Scenario D (buildout) as developed jointly by the two Towns is based on collection of wastewater within the proposed district and removal of wastewater loads from Lewis Bay watershed. Wastewater flows were developed under both current conditions as presented above (Section IX.7) and buildout conditions herein. Table IX-37 and Table IX-38 illustrate the overall change to septic and watershed loads resulting from this alternative. Based on the assumptions developed for this alternative, Table IX-39 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is exceeded at the sentinel station and infaunal check stations under build out conditions.

Table IX-37. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Build-Out Scenario D. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	-3.266	-112.3%
Uncle Roberts Cove	0.214	0.340	+59.0%
Mill Creek	13.570	-2.814	-120.7%
Hyannis Inner Harbor	6.847	4.688	-31.5%
Snows Creek	7.970	9.896	+24.2%
Stewarts Creek	21.564	25.307	+17.4%
Surface Water Sources			
Chase Brook	2.488	0.534	-78.5%
Mill Pond	10.425	9.726	-6.7%
Hospital Creek/Hyannis Inner	1.907	0.332	-82.6%

Table IX-38. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario D. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	5.181	-83.2%
Uncle Roberts Cove	0.540	0.715	+32.5%
Mill Creek	15.964	5.682	-64.4%
Hyannis Inner Harbor	12.153	12.762	+5.0%
Snows Creek	15.115	21.532	+42.5%
Stewarts Creek	38.992	53.959	+38.4%
Surface Water Sources			
Chase Brook	3.345	2.112	-36.9%
Mill Pond	15.038	21.814	+45.1%
Hospital Creek/Hyannis Inner	1.907	0.332	-82.6%

Table IX-39. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario D, 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)
Lewis Bay	5.181	13.507	24.546
Uncle Roberts Cove	0.715	0.759	11.505
Mill Creek	5.682	0.627	-1.404
Hyannis Inner Harbor	12.762	0.633	12.659
Snows Creek	21.532	-	-6.458
Stewarts Creek	53.959	0.236	-13.489
Surface Water Sources			
Chase Brook	2.112	-	-
Mill Pond	21.814	-	-
Hospital Creek/Hyannis Inner	0.332	-	-

Table IX-40. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario D), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.531**	**-3.4%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.482**	**-2.9%**
Hyannis Inner Harbor	BH-3	0.440	0.423	-3.7%
Snows Creek	BH-4	1.638	2.160	+31.9%
Lewis Bay	BH-5	0.387	0.374	-3.2%
Lewis Bay	BH-6	0.368	0.359	-2.5%
Stewarts Creek	BH-7	1.374	1.762	+28.2%
Lewis Bay	BHY-1	0.384	0.371	-3.3%
Lewis Bay	BHY-2	0.414	0.395	-4.7%
Lewis Bay	**BHY-3**	**0.407**	**0.386**	**-5.1%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.410**	**-4.8%**
Mill Creek	**MC-1**	**0.531**	**0.522**	**-1.7%**
Mill Creek	MC-2	0.473	0.441	-6.9%

IX.11 BUILD-OUT LOADING SCENARIO E

Scenario E (buildout) as developed jointly by the two Towns is based on collection of wastewater within the proposed district and treatment and discharge at the Hyannis WPCF. Wastewater flows were developed under both current conditions as presented above (Section IX.8) and buildout conditions herein. Table IX-41 and Table IX-42 illustrate the overall change to septic and watershed loads resulting from this alternative. Based on the assumptions developed for this alternative, Table IX-43 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is exceeded at the sentinel station and infaunal check stations under build out conditions.

Table IX-41. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Build-Out Scenario E. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	-3.266	-112.3%
Uncle Roberts Cove	0.214	0.340	+59.0%
Mill Creek	13.570	-2.814	-120.7%
Hyannis Inner Harbor	6.847	5.315	-22.4%
Snows Creek	7.970	12.847	+61.2%
Stewarts Creek	21.564	32.205	+49.3%
Surface Water Sources			
Chase Brook	2.488	0.534	-78.5%
Mill Pond	10.425	9.726	-6.7%
Hospital Creek/Hyannis Inner	1.907	0.332	-82.6%

Table IX-42. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario E. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.			
sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	5.181	-83.2%
Uncle Roberts Cove	0.540	0.715	+32.5%
Mill Creek	15.964	5.682	-64.4%
Hyannis Inner Harbor	12.153	13.389	+10.2%
Snows Creek	15.115	24.482	+62.0%
Stewarts Creek	38.992	60.858	+56.1%
Surface Water Sources			
Chase Brook	3.345	2.112	-36.9%
Mill Pond	15.038	21.814	+45.1%
Hospital Creek/Hyannis Inner	1.907	0.332	-82.6%

Table IX -43. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario E, 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)
Lewis Bay	5.181	13.507	24.585
Uncle Roberts Cove	0.715	0.759	11.703
Mill Creek	5.682	0.627	-1.404
Hyannis Inner Harbor	13.389	0.633	12.972
Snows Creek	24.482	-	-7.343
Stewarts Creek	60.858	0.236	-15.215
Surface Water Sources			
Chase Brook	2.112	-	-
Mill Pond	21.814	-	-
Hospital Creek/Hyannis Inner	0.332	-	-

Table IX-44. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario E), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.538**	**-2.0%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.488**	**-1.7%**
Hyannis Inner Harbor	BH-3	0.440	0.427	-2.8%
Snows Creek	BH-4	1.638	2.408	+47.0%
Lewis Bay	BH-5	0.387	0.377	-2.6%
Lewis Bay	BH-6	0.368	0.360	-2.1%
Stewarts Creek	BH-7	1.374	1.943	+41.5%
Lewis Bay	BHY-1	0.384	0.373	-2.9%
Lewis Bay	BHY-2	0.414	0.397	-4.2%
Lewis Bay	**BHY-3**	**0.407**	**0.388**	**-4.7%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.412**	**-4.3%**
Mill Creek	**MC-1**	**0.531**	**0.524**	**-1.4%**
Mill Creek	MC-2	0.473	0.443	-6.5%

IX.12 BUILD-OUT LOADING SCENARIO F

Scenario F (buildout) as developed jointly by the two Towns is based on collection of wastewater within the proposed district, treatment at the Hyannis WPCF, and discharge within an abandoned bog system to the east of Cape Cod Hospital. Wastewater flows were developed under both current conditions as presented above (Section IX.9) and buildout conditions herein. Table IX-45 and Table IX-46 illustrate the overall change to septic and watershed loads resulting from this alternative. Based on the assumptions developed for this alternative, Table IX-47 presents the various components of nitrogen loading for the Lewis Bay system. Despite the reductions in load related to the modeled sewer district, the threshold target (0.38 mg/L TN at BHY-3) is exceeded at the sentinel station and infaunal check stations under build out conditions.

Table IX-45. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling present loading conditions for Build-Out Scenario F. 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)	scenario septic load (kg/day)	threshold septic load % change
Lewis Bay	26.490	-3.266	-112.3%
Uncle Roberts Cove	0.214	0.340	+59.0%
Mill Creek	13.570	-2.814	-120.7%
Hyannis Inner Harbor	6.847	4.688	-31.5%
Snows Creek	7.970	9.896	+24.2%
Stewarts Creek	21.564	25.307	+17.4%
Surface Water Sources			
Chase Brook	2.488	0.534	-78.5%
Mill Pond	10.425	9.726	-6.7%
Hospital Creek/Hyannis Inner	1.907	9.384	+392.1%

Table IX-46. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario F. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Lewis Bay	30.855	5.181	-83.2%
Uncle Roberts Cove	0.540	0.715	+32.5%
Mill Creek	15.964	5.682	-64.4%
Hyannis Inner Harbor	12.153	12.762	+5.0%
Snows Creek	15.115	21.532	+42.5%
Stewarts Creek	38.992	53.959	+38.4%
Surface Water Sources			
Chase Brook	3.345	2.112	-36.9%
Mill Pond	15.038	21.814	+45.1%
Hospital Creek/Hyannis Inner	1.907	9.384	+392.1%

Table IX-47. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario F, 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)
Lewis Bay	5.181	13.507	25.067
Uncle Roberts Cove	0.715	0.759	11.980
Mill Creek	5.682	0.627	-1.404
Hyannis Inner Harbor	12.762	0.633	6.937
Snows Creek	21.532	-	-6.458
Stewarts Creek	53.959	0.236	-13.489
Surface Water Sources			
Chase Brook	2.112	-	-
Mill Pond	21.814	-	-
Hospital Creek/Hyannis Inner	9.384	-	-

Table IX-48. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario F), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Hyannis Inner Harbor	**BH-1**	**0.549**	**0.540**	**-1.8%**
Hyannis Inner Harbor	**BH-2**	**0.496**	**0.502**	**+1.3%**
Hyannis Inner Harbor	BH-3	0.440	0.456	+3.8%
Snows Creek	BH-4	1.638	2.180	+33.1%
Lewis Bay	BH-5	0.387	0.395	+2.3%
Lewis Bay	BH-6	0.368	0.371	+1.0%
Stewarts Creek	BH-7	1.374	1.768	+28.7%
Lewis Bay	BHY-1	0.384	0.387	+0.9%
Lewis Bay	BHY-2	0.414	0.414	+0.0%
Lewis Bay	**BHY-3**	**0.407**	**0.405**	**-0.6%**
Uncle Roberts Cove	**BHY-4**	**0.431**	**0.429**	**-0.5%**
Mill Creek	**MC-1**	**0.531**	**0.540**	**+1.6%**
Mill Creek	MC-2	0.473	0.460	-2.9%

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